

Pan-STARRS Pixel Processing : Detrending, Warping, Stacking

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ABSTRACT

The Pan-STARRS1 Science Consortium have carried out a set of imaging surveys using the 1.4 giga-pixel GPC1 camera on the PS1 telescope. As this camera is composed of many individual electronic readouts, and covers a very large field of view, great care was taken to ensure that the many instrumental effects were corrected to produce the most uniform detector response possible. We present the image detrending steps used as part of the processing of the data contained within the public release of the Pan-STARRS1 Data Release 1 (DR1). In addition to the single image processing, the methods used to transform the 375,573 individual exposures into a common sky-oriented grid are discussed, as well as those used to produce both the image stack and difference combination products.

Subject headings: Surveys:Pan-STARRS 1

1. Introduction and Survey Description

This is the third in a series of seven papers describing the Pan-STARRS1 Surveys, the data reduction techniques and the resulting data products. This paper (Paper III) describes the details of the pixel processing algorithms, including detrending, warping, and adding (to create stacked images) and subtracting (to create difference images) and resulting image

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products and their properties. Chambers et al. (2017, Paper I) provides an overview of the Pan-STARRS System, the design and execution of the Surveys, the resulting image and catalog data products, a discussion of the overall data quality and basic characteristics, and a brief summary of important results. Magnier et al. (2016a, Paper II) describes how the various data processing stages are organized and implemented in the Imaging Processing Pipeline (IPP), including details of the the processing database which is a critical element in the IPP infrastructure. Magnier et al. (2016b, Paper IV) describes the details of the source detection and photometry, including point-spread-function and extended source fitting models, and the techniques for “forced” photometry measurements. Magnier et al. (2017, Paper V) describes the final calibration process, and the resulting photometric and astrometric quality. Flewelling et al. (2016, Paper VI) describes the details of the resulting catalog data and its organization in the Pan-STARRS database. Huber et al. (2017, Paper VII) describes the Medium Deep Survey in detail, including the unique issues and data products specific to that survey. The Medium Deep Survey is not part of Data Release 1. (DR1) The Pan-STARRS1 filters and photometric system has already been described in detail in Tonry et al. (2012).

The Pan-STARRS 1 Science Survey uses the 1.4 giga-pixel GPC1 camera with the PS1 telescope on Haleakala Maui to image the sky north of -30° declination. The GPC1 camera is composed of 60 orthogonal transfer array (OTA) devices, each of which is an 8×8 grid of readout cells. This parallelizes the readout process, reducing the overhead in each exposure. However, as a consequence of this large number of individual detector readouts, many calibrations are needed to ensure the response is consistent across the entire field of view.

The Processing Version 3 (PV3) reduction represents the third full reduction of the Pan-STARRS archival data. The first two reductions were used internally for pipeline optimization and the development of the initial photometric and astrometric reference catalog (Magnier et al. 2017). The products from these reductions were not publicly released, but have been used to produce a wide range of scientific papers from the Pan-STARRS 1 Science Consortium members.

The Pan-STARRS image processing pipeline (IPP) is described elsewhere (Magnier et al. 2016a), but a short summary follows. The archive of raw exposures is stored on disk, with a database storing the metadata of exposure parameters. For the PV3 processing, large contiguous regions were defined, and the images for all exposures within that region launched for the CHIP stage processing. This stage performs the image detrending (described below in section 2), as well as the single epoch photometry (Magnier et al. 2016b), in parallel on the individual OTA device data. Following the CHIP stage is the CAMERA stage, in

which the astrometry and photometry for the entire exposure is calibrated by matching the detections against the reference catalog. This stage also performs masking updates based on the now-known positions and brightnesses of stars that create dynamic features (see Section 2.9.2 below). The WARP stage is the next to operate on the data, transforming the detector oriented CHIP stage images onto common sky oriented images that have fixed sky projections (Section 4). When all WARP stage processing is done for the region of the sky, STACK processing is performed (Section 5) to construct deeper, fully populated images from the set of WARP images that cover that region of the sky. Beyond the STACK stage, a series of additional stages are done that are more fully described in other papers. Transient features are identified in the DIFF stage, which takes input WARP and/or STACK data and performs image differencing (Section 6). Further photometry is performed in the STATISKEY and SKYCAL stages, which add extended source fitting to the point source photometry of objects detected in the STACK images, and calibrate the results against the reference catalog. The FULLFORCE stage takes the catalog output of the SKYCAL stage, and uses the objects detected in that to perform forced photometry on the individual WARP stage images. The details of these stages are provided in Magnier et al. (2016b).

The same reduction procedure described above is also performed in real time on new exposures as they are observed by the telescope. This process is largely automatic, with new exposures being downloaded from the summit to the main IPP processing cluster at the Maui Research and Technology Center in Kihei, and registered into the processing database. This triggers a new CHIP stage reduction for science exposures, advancing processing upon completion through to the DIFF stage. This allows the ongoing solar system moving object search to identify candidates for follow up observations within 24 hours of the initial set of observations (Wainscoat et al. 2015).

Section 2 provides an overview of the detrending process that corrects the instrumental signatures of GPC1, with details of the construction of those detrends in Section 3. An analysis of the algorithms used to complete the WARP (section 4), STACK (section 5), and DIFF (section 6) stage transformations of the image data to from the detector frame to a common sky frame, and the co-adding of those common sky frame images continues after the list of detrend steps. Finally, a discussion of the remaining issues and possible future improvements is presented in section 7.

Image products presented in figures have been mosaicked to arrange pixels as follows. Single cell images are arranged such that pixel (1,1) is at the lower left corner. Images mosaicked to the OTA level have cell xy00 in the lower left corner, with cells xy10, xy20, etc. sequentially to the right, and cells xy01, xy02, etc. sequentially to the top of this cell. Again, pixel (1,1) of cell xy00 is located in the lower left corner of the image. For mosaicks of the

full field of view, the OTAs are arranged as they see the sky. The lower left corner is the empty location where OTA70 would exist. Toward the right, the OTA labels decrease in X label, with the empty OTA00 located in the lower right. The OTA Y labels increase upward in the mosaic. The OTAs to the left of the midplane (OTA4Y-OTA7Y) are oriented with cell xy00 and pixel (1, 1) to the lower left of their position. Due to the electronic connections of the OTAs in the focal plane, the OTAs to the right of the midplane (OTA0Y-OTA3Y) are rotated 180 degrees, and are oriented with cell xy00 and pixel (1, 1) to the top right of their position.

Note: These papers are being placed on the arXiv.org to provide crucial support information at the time of the public release of Data Release 1 (DR1). We expect the arXiv versions to be updated prior to submission to the Astrophysical Journal in January 2017. Feedback and suggestions for additional information from early users of the data products are welcome during the submission and refereeing process.

2. GPC1 Detrend Details

Ensuring a consistent and uniform detector response across the three-degree diameter field of view of the GPC1 camera is essential to a well calibrated survey. Many standard image detrending steps are done for GPC1, with overscan subtraction removing the detector bias level, dark frame subtraction to remove temperature and exposure time dependent detector glows, and flat field correction to remove pixel to pixel response functions. We also construct fringe correction for the reddest data in the y_{P1} filter, to remove the interference patterns that arise in that filter due to the variations in the thickness of the detector surface.

These corrections, however, assume that the detector response is linear across the full range of values. This is not universally the case with GPC1, and this requires an additional set of detrending steps to remove these non-linear responses. The first of these is the **burntool** correction, which removes the persistence trails caused by the incomplete transfer of charge along the readout columns. This bright-end nonlinearity is generally only evident for the brightest stars, as only pixels that are at or beyond the saturation point of the detector have this issue. More widespread is the non-linearity at the faint end of the pixel range. Some readout cells and some readout cell edge pixels experience a sag relative to linear at low illumination, such that faint pixels appear fainter than expected. The correction to this requires amplifying the pixel values in these regions to match the expected model.

The final non-linear response issue has no good option for correction. Large regions of some OTA cells experience significant charge transfer issues, making them unusable for

science observations. These regions are therefore masked in processing, with these CTE regions making up the largest fraction of masked pixels on the detector. Other regions are masked for other reasons, such as static bad pixel features or temporary readout masking caused by issues in the camera electronics that make these regions unreliable. These all contribute to the detector mask, which is augmented in each exposure for dynamic features that are masked based on the astronomical features within the field of view.

For the PV3 processing, all detrending is done by the `ppImage` program. This program applies the detrends to the individual cells, and then an OTA level mosaic is constructed for the science image, the mask image, and the variance map image. The single epoch photometry is done at this stage as well. The following subsections (2.1 - 2.10) detail these detrending steps, presented in the order in which they are applied to the individual OTA image data.

2.1. Burntool / Persistence effect

Pixels that approach the saturation point on GPC1, which varies by readout with common values around 60000 DN, cause persistence problems on that and subsequent images. During the read out process of an image with such a bright pixel, some of the charge associated with it is not fully shifted down the detector column toward the amplifier. As a result, this charge remains in the starting cell, and is partially collected in subsequent shifts, resulting in a “burn trail” that extends from the center of the bright source away from the amplifier (vertically along the pixel columns toward the top of the cell).

This incomplete charge shifting in nearly full wells continues as each row is read out. This results in a remnant charge being deposited in the pixels that the full well was shifted through. In following exposures, this remnant charge leaks out, resulting in a trail that extends from the initial location of the bright source on the previous image towards the amplifier (vertically down along the pixel column). This remnant charge can remain on the detector for up to thirty minutes, requiring the locations of these “burns” be retained between exposures.

Both of these types of persistence trails are measured and optionally repaired via the `burntool` program. This program does an initial scan of the images, and identifies objects with pixel values brighter than a conservative threshold of 30000 DN. The trail from the peak of that object is fit with a one-dimensional power law in each pixel column above the threshold, based on empirical evidence that this is the functional form of this persistence effect. This also matches the expectation that a constant fraction of charge is incompletely

transferred at each shift beyond the persistence threshold. Once this fit is done, the model can be subtracted from the image, and the location of the star is stored in a table along with the exposure PONTIME, which denotes the number of seconds since the detector was last powered on, and provides an internally consistent time scale.

For subsequent exposures, the table associated with the previous image is read in, and after correcting trails from the stars on the new image, the positions of the bright stars from the table are used to check for remnant trails on the image. These are fit and subtracted using a one-dimensional exponential model, again based on empirical studies. If a significant model is found, then this location is retained in the image output table. If not, the old burn is allowed to expire.

The main concern with this method of correcting the persistence trails is that it is based on fits to the raw image data, which may have other signal sources not determined by the persistence effect. The presence of other stars or artifacts along the path of the burn can result in a poor model to be fit, resulting in either an over- or under-subtraction of the persistence burn. For this reason, the image mask is marked with a value indicating that this correction has been applied. These pixels are not fully excluded, but they are marked as suspect, which allows them to be excluded from consideration in subsequent stages, such as image stacking.

Another concern is that the cores of very bright stars are deformed by this process, as the burntool fitting subtracts flux from only one side of the star. As most stars that result in burns already have saturated cores, they are already ignored for the purpose of PSF determination and are flagged as saturated by the photometry reduction.

2.2. Overscan

Each cell on GPC1 has an overscan region that covers the first 34 columns of each row, and the last 10 rows of each column. No light lands on these pixels, so the image region is trimmed to exclude them. Each row has an overscan value subtracted, calculated by finding the median value of that row’s overscan pixels and then smoothing between rows with a three-row boxcar median.

2.3. Non-linearity Correction

The pixels of GPC1 are not uniformly linear at all flux levels. In particular, at low flux levels, some pixels have a tendency to sag relative to the expected linear value. This effect

is most pronounced along the edges of the detector cells, although some entire cells show evidence of this effect.

To correct this sag, we studied the flux behavior of a series of flat frames for a ramp of exposure times with approximate logarithmically equal spacing between 0.01s and 57.04s. As the exposure time increases, the flux on each pixel also increases in what is expected to be a linear manner. Each of these flat exposures in this ramp is overscan corrected, and then the median is calculated for each cell, as well as for the rows and columns within ten pixels of the edge of the science region. From these median values at each exposure time value, we can construct the expected trend by fitting a linear model, $f_{region} = G * t_{exp} + B$, to determine the gain, G , and the bias, B , for the region considered. This fitting was limited to only the range of fluxes between 12000 and 38000 counts, as these ranges were found to match the linear model well. This range avoids the non-linearity at low fluxes, as well as the possibility of high-flux non-linearity effects.

We store the average flux measurement and deviation from the linear fit for each exposure time for all regions on all detector cells in the linearity detrend look up tables. When this is applied to science data, these lookup tables are loaded, and a linear interpolation is performed to determine the correction needed for the flux in that pixel. This look up is performed for both the row and column of each pixel, to allow the edge correction to be applied where applicable, and the full cell correction elsewhere. The average of these two values is then applied to the pixel value, reducing the effects of pixel nonlinearity.

This non-linearity effect appears to be stable in time for the majority of the detector pixels, with little evident change over the survey duration. However, as the non-linearity is most pronounced at the edges of the detector cells, those are the regions where the correction is most likely to be incomplete. Because of this fact, most pixels in the static mask with either the DARKMASK or FLATMASK bit set are found along these edges. As the non-linearity correction is unable to reliably restore these pixels, they produce inconsistent values after the dark and flat have been applied, and are therefore rejected.

2.4. Dark/Bias Subtraction

The dark model we make for GPC1 considers each pixel individually, independent of any neighbors. To construct this model, we fit a multi-dimensional model to the array of input pixels from a randomly selected set of 100-150 overscan and non-linearity corrected dark frames chosen from a given date range. The model fits each pixel as a function of the exposure time t_{exp} and the detector temperature T_{chip} of the input images such that

$\text{dark} = a_0 + a_1 t_{\text{exp}} + a_2 T_{\text{chip}} t_{\text{exp}} + a_3 T_{\text{chip}}^2 t_{\text{exp}}$. This fitting uses two iterations to produce a clipped fit, rejecting at the 3σ level. The final coefficients a_i for the dark model are stored in the detrend image. The constant a_0 term includes the residual bias signal after overscan subtraction, and as such, a separate bias subtraction is not necessary.

Applying the dark model is simply a matter of calculating the response to the exposure time and detector temperature for the image to be corrected, and subtracting the resulting dark signal from the image.

2.4.1. Time evolution

The dark model is not consistently stable over the full survey, with significant drift over the course of multiple months. Some of the changes in the dark can be attributed to changes in the voltage settings of the GPC1 controller electronics, but the majority seem to be the result of some unknown parameter. We can separate the dark model history of GPC1 into three epochs. The first epoch covers all data taken prior to 2010-01-23. This epoch used a different header keyword for the detector temperature, making data from this epoch incompatible with later dark models.

The second epoch covers data between 2010-01-23 and 2011-05-01, and is characterized by a largely stable but oscillatory dark solution. There are two modes that the dark model switches between apparently at random. No clear cause has been established for the switching, but there are clear differences between the two modes that require the observation dates to be split to use the model that is most appropriate.

The initial evidence of these two modes comes from the discovery of a slight gradient along the rows of certain cells. This is a result of a drift in the bias level of the detector as it is read out. An appropriate dark model should remove this gradient entirely. For these two modes, the direction of this bias drift is different, so a single dark model generated from all dark images in the time range over corrects the positive-gradient mode, and under corrects the negative-gradient mode. Upon identifying this two-mode behavior, and determining the dates each mode was dominant, two separate dark models were constructed from appropriate “A” and “B” mode dark frames. Using the appropriate dark minimizes the effect of this bias gradient in the dark corrected data.

The bias drift gradients of the mode switching can be visualized in Figure 5. This figure shows the image profile along the x-pixel axis binned along the full y-axis of the first row of cells. The raw data is shown, illustrating the positional dependence the dark signal has on the image values. In addition, both the correct B-mode dark and incorrect A-mode dark

have been applied to this image, showing that although both correct the bulk of the dark signal, using the incorrect mode creates larger intensity gradients.

After 2011-05-01, the two-mode behavior of the dark disappears, and is replaced with a slow observation date dependent drift in the magnitude of the gradient. This drift is sufficiently slow that we have modeled it using three observation date independent dark model for different date ranges. These darks cover the range from 2011-05-01 to 2011-08-01, 2011-08-01 to 2011-11-01, and 2011-11-01 and on. The reason for this time evolution is unknown, but as it is correctable with a small number of dark models, this does not significantly impact detrending.

2.4.2. Video Dark

The dark signal is stronger in cell corners due to glow from the read-out amplifiers. The standard dark model corrects this for most observations. However, as mentioned above, when a cell is repeatedly read in video mode, the dark model for the OTA containing it changes. Surprisingly, added reads for the video cell do not amplify the amplifier glow, but rather decrease the dark signal in these regions. As a result, using the standard dark model on the data for these OTAs results in oversubtraction of the corner glow.

Video darks have been constructed to eliminate the effect this observational change has on the final image quality. This was done by running the standard dark construction process on a series of dark frames that have had the video signal enabled for some cells. GPC1 can only run video signals on a subset of the OTAs at a given time. This requires two passes to enable the video signal across the full set of OTAs that support video cells. This is convenient for the process of creating darks, as those OTAs that do not have video signals enabled create standard dark models, while the video dark is created for those that do.

This simultaneous construction of video and standard dark models is useful, as it provides the ability to isolate the response on the standard dark from the video signals. Isolating this response is essential for attempting to create archival video darks. We only have raw video dark frame data after 2012-05-16, when this problem was initially identified, so any data prior to that can not be directly corrected for the video dark signal. Isolating the video signal response allows linear corrections to the pre-existing standard dark models for archival data. Testing this shows that constructing a video dark for older data simply as $VD_{2009} = D_{2009} - D_{Modern} + VD_{Modern}$ produces a satisfactory result that does not over subtract the amplifier glow. This is shown in figure 6, which shows video cells from before 2012-05-16, corrected with both the standard and video darks, with the early video dark

constructed in such a manner.

2.5. Noisemap

Based on a study of the positional dependence of all detected sources, we have discovered that the cells in GPC1 do not have uniform noise characteristics. Instead, there is a gradient along the pixel rows, with the noise generally higher away from the read out amplifier (higher cell x pixel positions). This is likely an effect of the row-by-row bias issue discussed below. This gradient causes the read noise to increase as the row is read out. As a result of this increased noise, more sources are detected in the higher noise regions when the read noise is assumed constant across the readout. Read noise is the

To mitigate this noise gradient, we constructed an initial set of noisemap images by measuring the median variance on bias frames. The variance is calculated in boxes of 20x20 pixels, and then linearly interpolated to cover the full image.

Unfortunately, due to correlations within this noise, the variance measured from the bias images does not fully remove the positional dependence of objects that are detected. This simple noisemap underestimates the noise observed when the image is filtered during the object detection process. This filtering convolves the background noise with a PSF, which has the effect of amplifying the correlated peaks in the noise. This amplification can therefore boost background fluctuations above the threshold used to select real objects, contaminating the final object catalogs.

In the detection process, we expect false positives at a rate equal to the one-tailed probability beyond the detection threshold. For these tests, only detections measured at the $\sigma_{thresh} = 5\sigma$ level are used, to match that used in the photometry on science data. This probability can be converted into a number of false number by considering a given area. As the detections must be isolated to not be detected as an extended object, this area must be reduced by the area a given PSF occupies. Combining this, we find that we expect a probability $P = 1 - \Phi_{normal}(5) = \frac{1}{2} \text{erfcinv}\left(\frac{5}{\sqrt{2}}\right)$, and an area given N exposures of area $X \times Y$, $A = \frac{X \times Y \times N}{A_{PSF}}$. For a typical 1" seeing, A_{PSF} is approximately 16 pixels. Using this model for the false positives, we found that the added read noise was insufficient to account for the observed false positive rate. Inverting this relation, we can measure σ_{obs} , the true threshold level based on the number of false positives observed. This σ_{obs} is the combined to form a boost factor $B = \sigma_{thresh}/\sigma_{obs}$ that amplifies the noisemap to match the observed false detection rate.

The row-to-row variations that contribute to the extra noise are related to the dark

model, and because of this, as the dark model changes, the effective noise also changes. To ensure that the noisemap accurately matches the true noise level, we have created different noisemap models for the three major time ranges of the dark model. We do not see any strong evidence that the noisemaps have the A/B modes visible in the dark, and so we do not generate different models for each individual dark model. The additional pixel-to-pixel variance from this noisemap is added to the Poissonian variance to form the science variance image generated by the CHIP processing.

2.6. Flat

Determining a flat field correction for GPC1 is a challenging endeavor, as the wide field of view makes it difficult to construct a uniformly illuminated image. Using a dome screen is not possible, as the variations in illumination and screen rigidity create large scatter between different images that are not caused by the detector response function. Because of this, we use sky flat images taken at twilight, which are more consistently illuminated than screen flats. We calculate the mean of these images to determine the initial flat model.

From this starting skyflat model, we construct a photometric correction to remove the effect of the illumination differences over the detector surface. This is done by dithering a series of science exposures with a given pointing. By fully calibrating these exposures with the initial flat model, and then comparing the measured fluxes for the same star as a function of position on the detector, we can determine position dependent scaling factors. From the set of scaling factors for the full catalog of stars observed in the dithered sequence, we can construct a model of the error in the initial flat model as a function of detector position. Applying a correction that reduces the amplitude of these errors produces a flat field model that better represents the true detector response.

In addition to this flat field applied to the individual images, the ubercal process used to calibrate the database of all detections (Schlafly et al. 2012) constructs internal “flat field” corrections. Although a single set of image flat fields was used for the entire PV3 survey, five separate “seasons” of database flat fields were needed to ensure proper calibration. This indicates that the flat field response is not completely fixed in time. More details on this process are contained in Magnier et al. (2017).

2.7. Pattern correction

Due to detector specific issues that are not cleanly removed by the dark model, we have a set of “pattern” corrections that are applied to some selection of the OTAs in the camera. This is done to reduce the effect that detector differences have on the measured astronomical signal that are not stable enough to be corrected with a static model. Because of this, the pattern corrections attempt to identify and correct the detector issues based on appropriate filtering the individual science exposures.

The PATTERN.ROW correction is used to remove any remaining row-by-row bias variation, and the PATTERN.CONTINUITY correction attempts to ensure that the cells of a given OTA are consistent with the other cells on that OTA.

2.7.1. Pattern Row

As discussed above in the dark and noisemap sections, certain detectors have significant bias offsets between adjacent rows, caused by noise in the camera control electronics. The magnitude of these offsets increases as the distance from the readout amplifier increases, resulting in horizontal streaks that are more pronounced along the large x pixel edge of the cell. As the level of the offset is apparently random between exposures, the dark correction cannot fully remove this structure from the images, and the noisemap value only indicates the level of the average variance added by these bias offsets. Therefore, we apply the PATTERN.ROW correction in an attempt to mitigate the offsets and correct the image values. To force the rows to agree, a second order clipped polynomial is fit to each row in the cell. Four fit iterations are run, and pixels 2.5σ deviant are excluded from subsequent fits, to minimize the effect stars and other astronomical signals have. This final trend is then subtracted from that row. Simply doing this subtraction will also have the effect of removing the background sky level. To prevent this, the constant and linear terms for each row are stored, and linear fits are made to these parameters as a function of row, perpendicular to the initial fits. This produces a plane that is added back to the image to restore the background offset and any linear ramp that exists in the sky.

These row-by-row variations have the largest impact on data taken in the g_{P1} filter, as the read noise is the dominant noise source in that filter. At longer wavelengths, the noise from the Poissonian variation in the sky level increases. Although the PATTERN.ROW correction is still applied to data taken in the other filters,

This correction was required on all cells on all OTAs prior to 2009-12-01, at which point a modification of the camera electronics reduced the scale of the row-by-row offsets for the

majority of the OTAs. As a result, we only apply this correction to the cells where it is still necessary, as shown in Figure 7. A list of these cells is listed in Table 1.

Although this correction does largely resolve the row-by-row offset issue in a satisfactory way, large and bright astronomical objects can bias the fit significantly. This results in an oversubtraction of the offset near these objects. As the offsets are calculated on the pixel rows, this oversubtraction is not uniform around the object, but is preferentially along the horizontal x axis of the object. Most astronomical objects are not significantly distorted by this, with this only becoming an issue for only bright objects comparable to the size of the cell ($598 \text{ pixels} = 150''$).

2.7.2. Pattern Continuity

After previous attempts to ensure that adjacent cells on an OTA matched background levels were insufficient in many situations, we designed a replacement correction that would reduce the background distortion for large objects. In addition, studies of the background level illustrated that the row-by-row bias can introduce small background gradient variations along the rows of the cells that is not stable enough to be completely fit by the dark model. This common feature across the columns of cells results in a “saw tooth” pattern horizontally across an OTA, and as the background model fits a smooth sky level, this induces over and under subtraction at the cell boundaries.

The PATTERN.CONTINUITY correction, attempts to match the edges of a cell to those of its neighbors. For each cell, a thin box 10 pixels wide on each edge is extracted and the median value of unmasked values calculated for that box. These median values are then used to construct a vector of differences $\Delta_i = \sum_j \text{Edge}_i - \text{Edge}_j$, along with a matrix of associations $A_{i,i'} = \sum_j \delta(i, j)\delta(j, i')$ denoting which cell boundaries are adjacent. By solving the system $Ax = \Delta$, we find the set of offsets x_i to be applied to each cell to ensure the minimum differences between all cell edges and their neighbors.

For OTAs that initially show the saw tooth pattern, the effect of this correction is to align the cells into a single ramp, at the expense of the absolute background level. However, as we subtract off a smooth background model prior to doing photometry, these deviations from an absolute sky level are unimportant. The fact that the final ramp is smoother than it would be otherwise also allows for the background subtracted image to more closely match the astronomical sky, without significant errors at cell boundaries. An example of the effect of this correction on an image profile is shown in Figure 5.

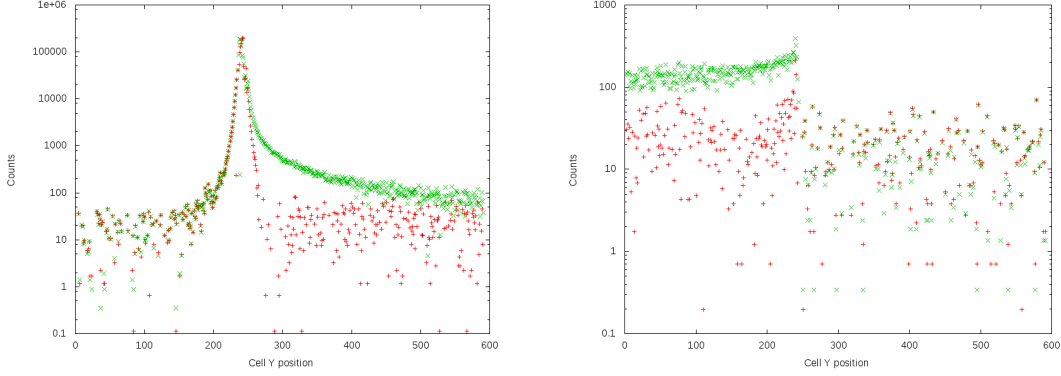


Fig. 1.— Example of a profile cut along the y-axis through a bright star on exposure o5677g0123o OTA11 in cell xy60 (left panel) and on the subsequent exposure o5677g0124o (right panel). In both figures, the green points show the image corrected with all appropriate detrending steps, but without burntool applied, illustrating the amplitude of the persistence trails. The red points show the same data after the burntool correction, which reduces the impact of these features. Both exposures are in the g_{P1} filter with exposure times of 43s

Table 1. Cells which have PATTERN.ROW correction applied

OTA	Cell columns	Additional cells
OTA11		xy02, xy03, xy04, xy07
OTA14		xy23
OTA15	0	
OTA27	0, 1, 2, 3, 7	
OTA31	7	
OTA32	3, 7	
OTA45	3, 7	
OTA47	0, 3, 5, 7	
OTA57	0, 1, 2, 6, 7	
OTA60		xy55
OTA74	2, 7	

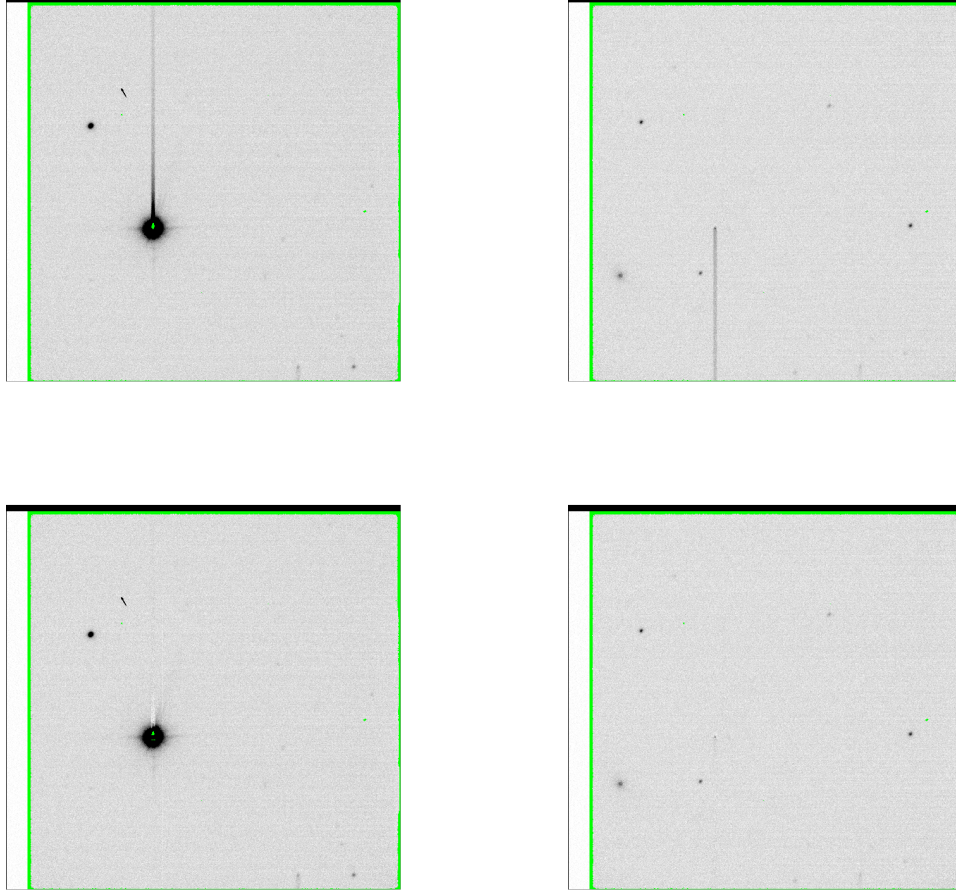


Fig. 2.— Example of OTA11 cell xy60 on exposures o5677g0123o (left) and o5677g0124o (right). The top panels show the image with all appropriate detrending steps, but without burntool, and the bottom show the same with burntool applied. There is some slight over subtraction in fitting the initial trail, but the impact of the trail is greatly reduced in both exposures.

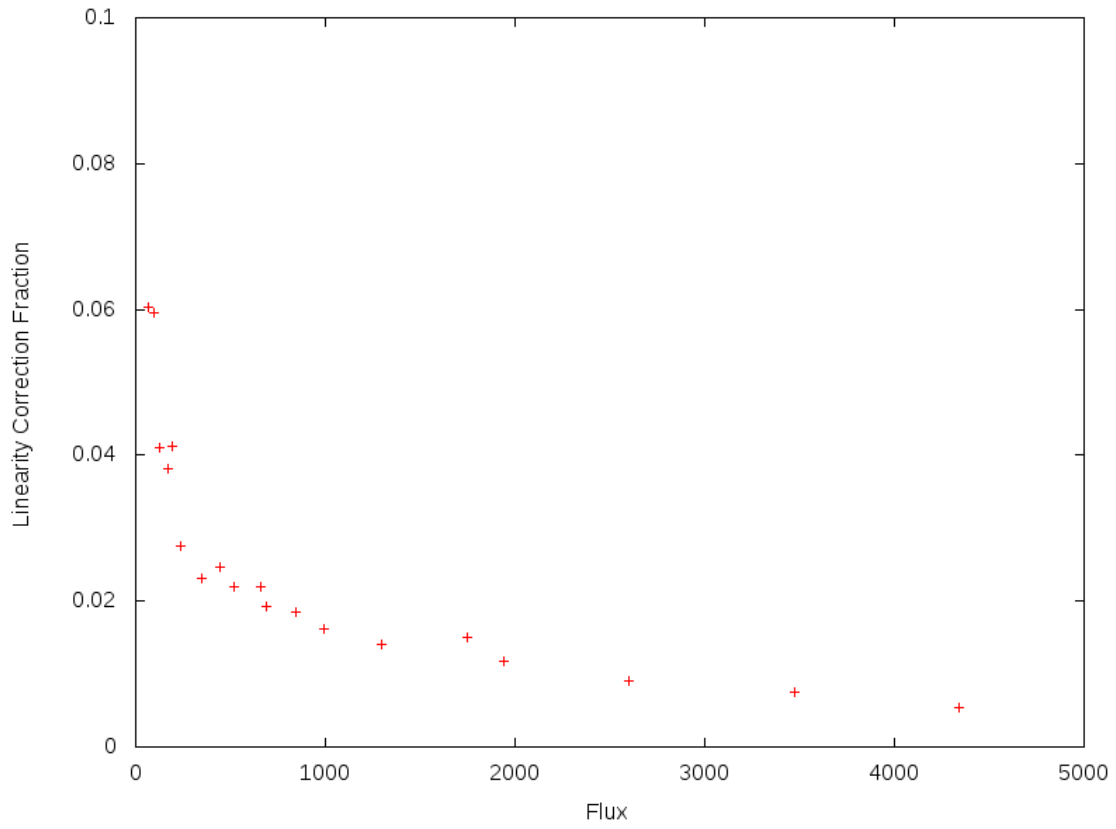


Fig. 3.— Example plot of the linearity correction as a fraction of observed flux for OTA27, cell xy16.

2.8. Fringe correction

Due to variations in the thickness of the detectors, we observe interference patterns at the infrared end of the filter set, as the wavelength of the light becomes comparable to the thickness of the detectors. Visually inspecting the images shows that the fringing is most prevalent in the y_{P1} filter images, with negligible fringing in the other bands. As a result of this, we only apply a fringe correction to the y_{P1} filter data.

The fringe used for PV3 processing was constructed from a set of 20 120s science exposures. These exposures are overscan subtracted, and corrected for non-linearity, and have the dark and flat models applied. These images are smoothed with a Gaussian kernel with $\sigma = 2$ pixels to minimize pixel to pixel noise. The fringe image data is then constructed by calculating the clipped mean of the input images with two iteration of clipping at the 3σ level.

A coarse background model for each cell is constructed by calculating the median on a 3×3 grid (approximately 200×200 pixels each). A set of 1000 randomly selected points are then selected on the fringe image for each cell, and a median calculated for this position in a 10×10 pixel box, with the background level subtracted. These sample locations provide scale points to allow the amplitude of the measured fringe to be compared to that found on science images.

To apply the fringe, the same sample locations are measured on the science image to determine the relative strength of the fringing in that particular image. A least squares fit between the fringe measurements and the corresponding measurements on the science image provides the scale factor multiplied to the fringe before it is subtracted from the science image.

2.9. Masking

2.9.1. Static Masks

Due to the large size of the detector, it is expected that there are a number of pixel defects that do not have the detection sensitivity on par with their neighbors. To remove these pixels, we have constructed a static mask that identifies the known defects. This mask is constructed in three phases.

First, a CTEMASK is constructed to mask out regions in which the charge transfer efficiency is low compared to the rest of the detector. Twenty-five of the sixty OTAs in

GPC1 show some evidence of CTE issues, with this pattern appearing (to varying degrees) in roughly triangular patches on the OTA due to defects in the semiconductor manufacturing. To generate the mask for these regions, a sample set of 26 evenly illuminated flat field images were measured to produce a map of the image variance in 20x20 pixel bins. As the flat image is expected to illuminate the image uniformly, the expected variances in each bin should be Poissonian distributed with the flux level. However, in regions with CTE issues, adjacent pixels are not independent, as the charge in those pixels is more free to spread. This reduces the pixel-to-pixel differences, resulting in a lower than expected variance. All regions with variance less than half the average image level are added to the static CTEMASK.

The next step of mask construction is to examine the flat and dark models, and exclude pixels that appear to be poorly corrected by these models. The DARKMASK process looks for pixels that are more than 8σ discrepant in 10% of the 100 input dark frame images after those images have had the dark model applied to them. These pixels are assumed to be unstable with respect to the dark model, and have the DARK bit set in the static mask, indicating that they are unreliable in scientific observing. Similarly, the FLATMASK process looks for pixels that are 3σ discrepant in the same fraction of 16 input flat field images after both the dark and flat models have been applied. Those pixels that do not follow the flat field model of the rest of image are assigned the FLAT mask bit in the static mask, removing the pixels that cannot be corrected to a linear response.

The final step of mask construction is to examine the detector for bright columns and other static pixel issues. This is first done by processing a set of 100 i_{P1} filter science images in the same fashion as for the DARKMASK. A median image is constructed from these inputs along with the per-pixel variance. These images are used to identify pixels that have unexpectedly low variation between all inputs, as well as those that significantly deviate from the global median value. Once this initial set of bad pixels is identified, a 3×3 pixel triangular kernel is convolved with the initial set, and any convolved pixel with value greater than 1 is assigned to the static mask. This does an excellent job of removing the majority of the problem pixels. A subsequent manual inspection allows human interaction to identify other inconsistent pixels including the vignetted regions around the edge of the detector.

Figure 2.9.1 shows an example of the static mask for the full GPC1 field of view. Table 2 lists the bit mask values used for the different sources of masking.

Table 2. GPC1 Mask Values

Mask Name	Mask Value	Description
DETECTOR	0x0001	A detector defect is present.
FLAT	0x0002	The flat field model does not calibrate the pixel reliably.
DARK	0x0004	The dark model does not calibrate the pixel reliably.
BLANK	0x0008	The pixel does not contain valid data.
CTE	0x0010	The pixel has poor charge transfer efficiency.
SAT	0x0020	The pixel is saturated.
LOW	0x0040	The pixel has a lower value than expected.
SUSPECT	0x0080	The pixel is suspected of being bad.
BURNTOL	0x0080	The pixel contain an burnttool repaired streak.
CR	0x0100	A cosmic ray is present.
SPIKE	0x0200	A diffraction spike is present.
GHOST	0x0400	An optical ghost is present.
STREAK	0x0800	A streak is present.
STARCORE	0x1000	A bright star core is present.
CONV.BAD	0x2000	The pixel is bad after convolution with a bad pixel.
CONV.POOR	0x4000	The pixel is poor after convolution with a bad pixel.
MARK	0x8000	An internal flag for temporarily marking a pixel.

2.9.2. *Dynamic masks*

In addition to the static mask that removes the constant detector defects, we also generate a set of dynamic masks that change with the astronomical features in the image. These masks are advisory in nature, and do not completely exclude the pixel from further processing consideration. The first of these dynamic masks is the burnttool advisory mask mentioned above. These pixels are included for photometry, but are rejected more readily in the stacking and difference image construction, as they are more likely to have small deviations due to imperfections in the burnttool correction.

The remaining dynamic masks are not generated until the IPP CAMERA stage, at which point all object photometry is complete, and an astrometric solution is known for the exposure. This added information provides the positions of bright sources based on the reference catalog, including those that fall slightly out of the detector field of view or within the inter chip gaps, where internal photometry may not identify them. These bright sources are the origin for many of the image artifacts that the dynamic mask identifies and excludes.

Electronic crosstalk ghosts

Due to electrical crosstalk between the flex cables connecting the individual detector OTA devices, ghost objects can be created by the presence of a bright source at a different position on the camera. Table 3 summarizes the list of known crosstalk rules, with an estimate of the magnitude difference between the source and ghost. For all of the rules, any cell v within the specified column of cells on any of the OTAs in the specified column of OTAs Y creates the ghost in the same v and Y in the target column of cells and OTAs. In each of these cases, a source object with an instrumental magnitude brighter than -14.47 creates a ghost object many orders of magnitude fainter at the target location. The cell (x,y) pixel coordinate is identical between source and ghost, as a result of the transfer occurring as the devices are read. A circular mask is added to the ghost location with radius $R = 3.44(-14.47 - m_{source,instrumental})$ pixels. Any objects in the photometric catalog found at the location of the ghost mask have the GHOST mask bit set, marking the object as a likely ghost. The majority of the crosstalk rules are bi-directional, with a source in either position creating a ghost at the corresponding crosstalk target position. The two faintest rules are uni-directional, due to differences in the electronic path for the crosstalk.

For the very brightest sources ($m_{instrumental} < -15$), there can be crosstalk ghosts between all columns of cells during the readout. These “bleed” ghosts were originally identified as ghosts of the saturation bleeds appearing in the neighboring cells, and as such, the masking for these objects puts a rectangular mask down from top to bottom of cells in all columns

that are in the same row of cells as the bright source. The width of this box is a function of the source magnitude, with $W = 5 * (-15 - m_{source,instrumental})$ pixels.

Optical ghosts

Due to imperfections in the anti-reflective coating on the optical surfaces of GPC1, bright sources can also result in large out of focus objects, particularly in the g_{P1} filter data. These objects are the result of light reflecting back off the surface of the detector, reflecting again off the lower surfaces of the optics (particularly the L1 corrector lens), and then back down onto the focal plane. Due to the extra travel distance, the resulting source is out of focus and elongated along the radial direction of the camera focal plane. These optical ghosts can be modeled in the focal plane coordinates (L,M) which has its origin at the center of the focal plane. In this system, a bright object at location (L,M) on the focal plane creates a reflection ghost on the opposite side of the optical axis at (-L,-M). The exact location is fit as a third order polynomial in the focal plane L and M directions (as listed in Table 4). An elliptical annulus mask is constructed at the expected ghost location, with the major and minor axes defined by linear functions of the ghost distance from the optical axis, and oriented with the ellipse major axis is along the radial direction (Table 5). All stars brighter than a filter-dependent threshold (listed in Table 6) have such masks constructed.

Optical glints

Prior to 2010-08-24, a reflective surface at the edge of the camera aperture was incompletely screened to light passing through the telescope. Sources brighter than $m_{inst} = -21$ that fell on this reflective surface resulted in light being scattered across the detector surface in a long narrow glint. This surface was physically masked on 2010-08-24, removing the possibility of glints in subsequent data, but that taken prior have an advisory dynamic mask constructed when a reference source falls on the focal plane within one degree of the detector edge. This mask is 150 pixels wide, with length $L = 2500 (-20 - m_{inst})$ pixels. These glint masks are constructed by selecting sufficiently bright sources in the reference catalog that fall within rectangular regions around each edge of the GPC1 camera. These regions are separated from the edge of the camera by 17 arcminutes, and extend outwards an additional degree.

Diffraction Spikes and Saturated Stars

Bright sources also form diffraction spikes that are dynamically masked. These are filter independent, and are modeled as rectangles with length $L = 10^{0.096*(7.35 - m_{instrumental})} - 200$

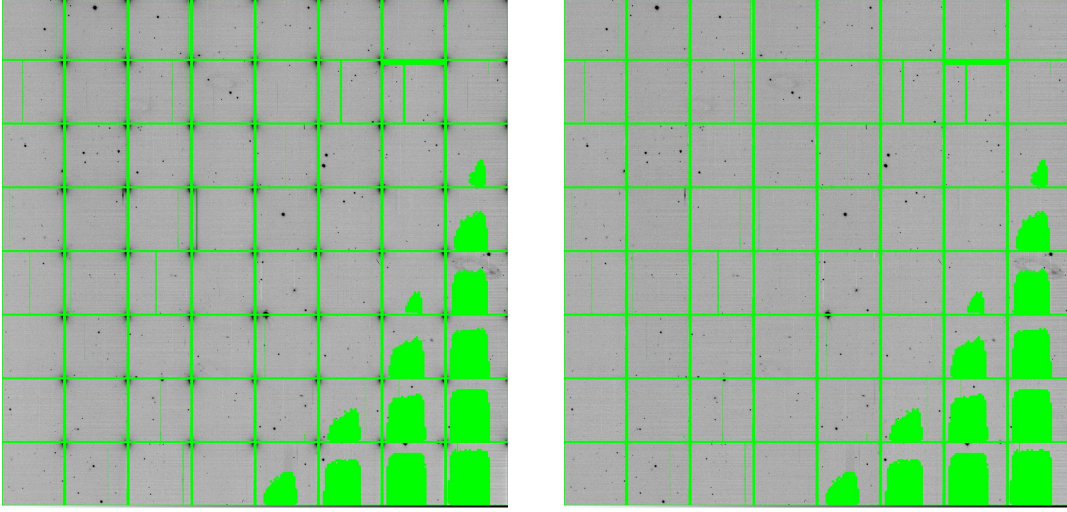


Fig. 4.— An example of the dark model application to exposure o5677g0123o, OTA23 (2011-04-26, 43s g_{P1} filter). The left panel shows the image data mosaicked to the OTA level, and has had the static mask applied, the overscan subtracted, and the detector non-linearity corrected. The right panel, shows the same exposure with the dark applied in addition to the processing shown on the left.

Table 3. GPC1 Crosstalk Rules

Type	Source OTA/Cell	Ghost OTA/Cell	Δm
Inter-OTA	OTA2Y XY3v	OTA3Y XY3v	6.16
	OTA3Y XY3v	OTA2Y XY3v	
	OTA4Y XY3v	OTA5Y XY3v	
	OTA5Y XY3v	OTA4Y XY3v	
Intra-OTA	OTA2Y XY5v	OTA2Y XY6v	7.07
	OTA2Y XY6v	OTA2Y XY5v	
	OTA5Y XY5v	OTA5Y XY6v	
	OTA5Y XY6v	OTA5Y XY5v	
One-way	OTA2Y XY7v	OTA3Y XY2v	7.34
	OTA5Y XY7v	OTA4Y XY2v	

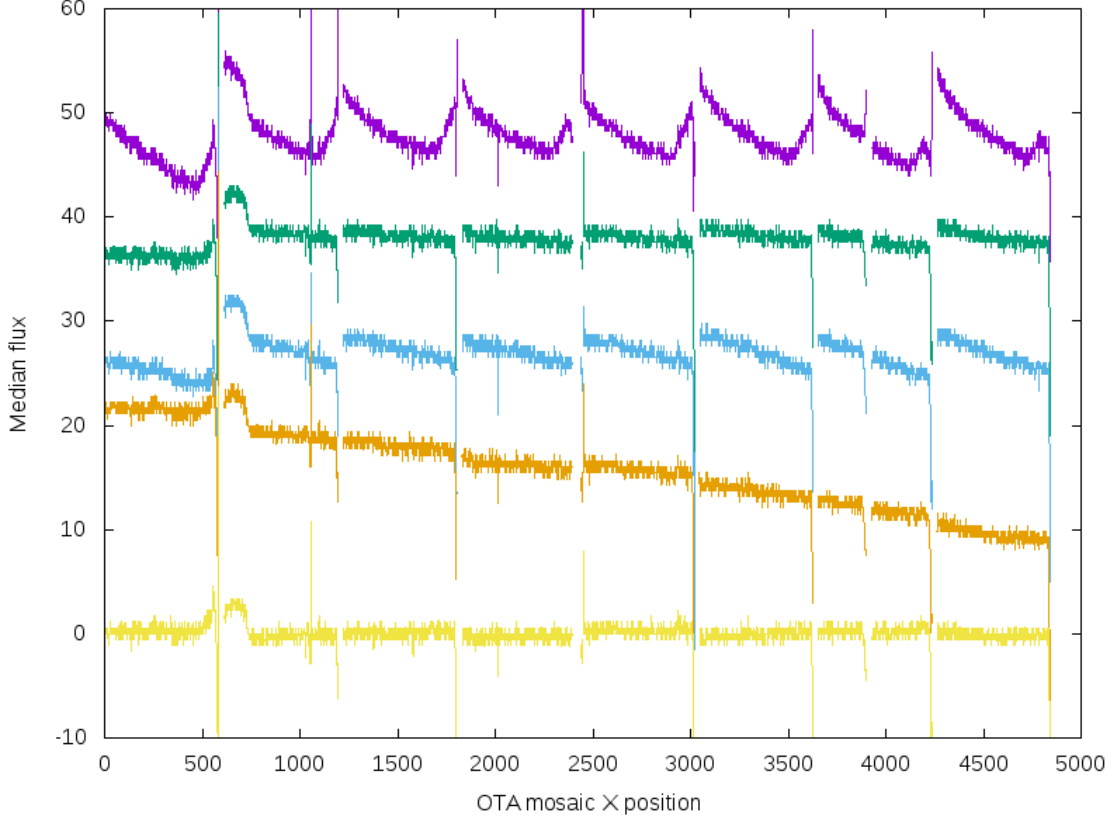


Fig. 5.— Example showing a profile cut across exposure o5676g0195, OTA67 (2011-04-25, 43s g_{P1} filter). The entire first row of cells (xy00-xy07) have had a median calculated along each pixel column on the OTA mosaicked image. Arbitrary offsets have been applied to shift the curves to not overlap. The top curve (in purple) shows the initial raw profile, with no dark model applied. The next curve (in green) shows the smoother profile after applying the correct B-mode dark model. Applying the incorrect A-mode dark results in the blue curve, which shows a significant increase in gradients across the cells. The orange curve shows the result of the PATTERN.CONTINUITY correction. Although this creates a larger gradient across the mosaicked images, it decreases the cell-to-cell level changes. The final yellow curve shows the final image profile after all detrending and background subtraction, and has not had an offset applied. The bright source at the cell xy00 to xy01 transition is a result of a large optical ghost, which due to the area covered, increases the median level more than the field stars.

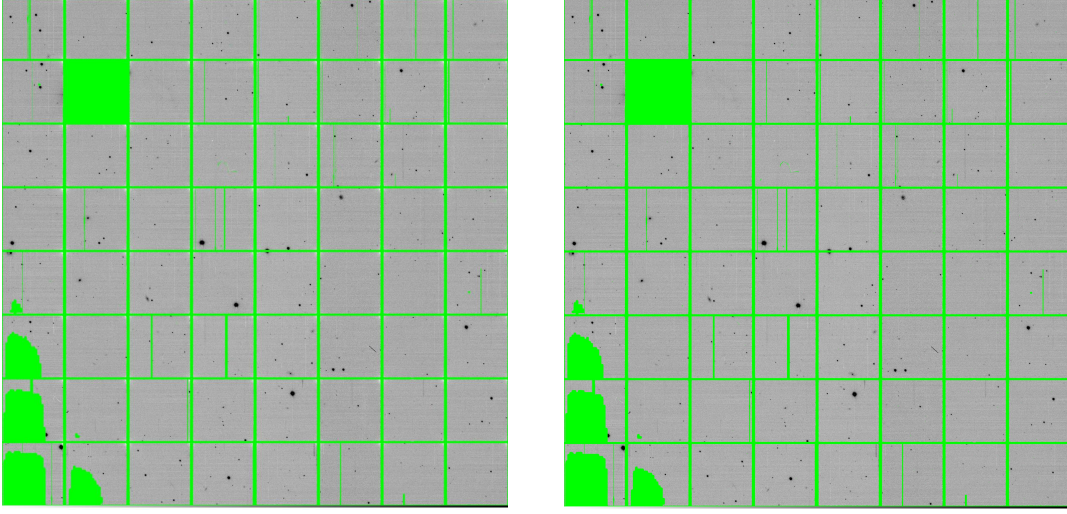


Fig. 6.— An example of the video dark model application to exposure o5677g0123o, OTA22 (2011-04-26, 43s g_{P1} filter), which has a video cell located in cell xy16. The left panel shows the image data mosaicked to the OTA level, and has had the static mask applied, the overscan subtracted, the detector non-linearity corrected, and a regular dark applied. The right panel, shows the same exposure with a video dark applied instead of the standard dark. The main impact of this change is the improved correction of the corner glows, which are over subtracted with the standard dark.

Table 4. Optical Ghost Center Transformations

Polynomial Term	L center	M center
x^0y^0	-1.215661e+02	2.422174e+01
x^1y^0	1.321875e-02	4.170486e-04
x^2y^0	-4.017026e-09	-1.934260e-08
x^3y^0	1.148288e-10	-1.173657e-12
x^0y^1	-1.908074e-03	1.189352e-02
x^1y^1	8.479150e-08	-9.256748e-08
x^2y^1	1.635732e-11	1.140772e-10
x^0y^2	2.625405e-08	8.123932e-08
x^1y^2	1.125586e-10	1.328378e-11
x^0y^3	2.912432e-12	1.170865e-10

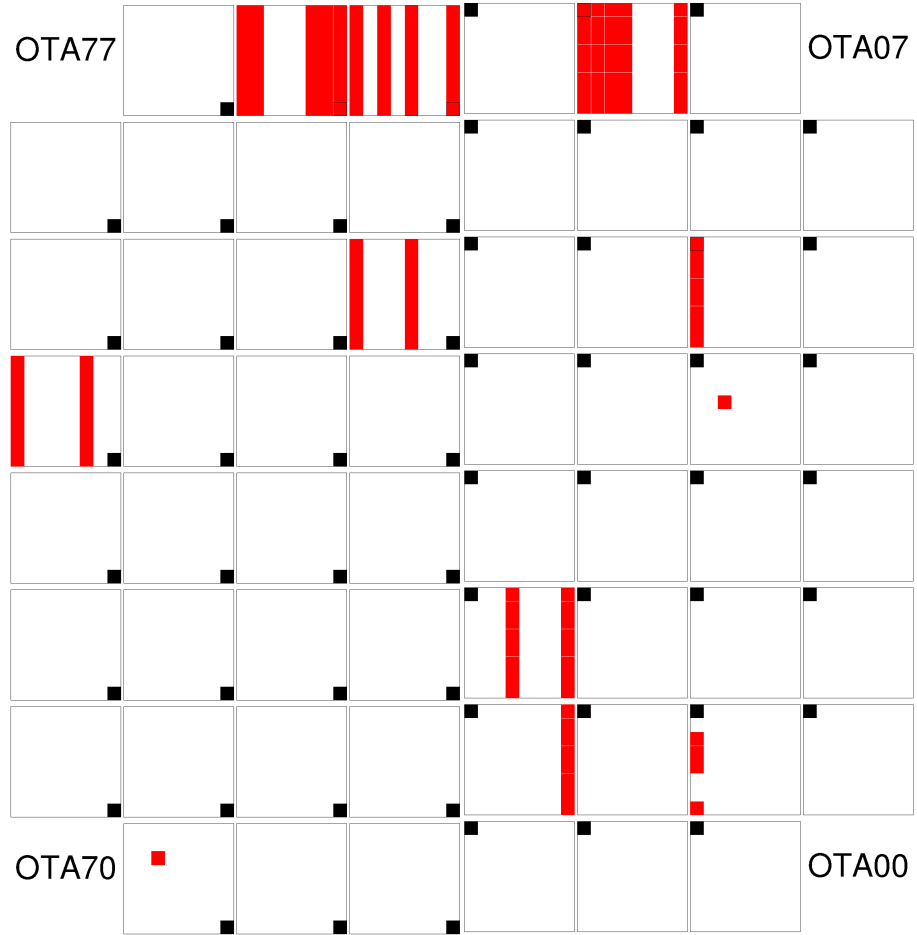


Fig. 7.— Diagram illustrating in red which cells on GPC1 require the PATTERN.ROW correction to be applied. The footprint of each OTA is outlined, and cell xy00 is marked with either a filled box or an outline. The labeling of the non-existent corner OTAs is provided to orient the focal plane.

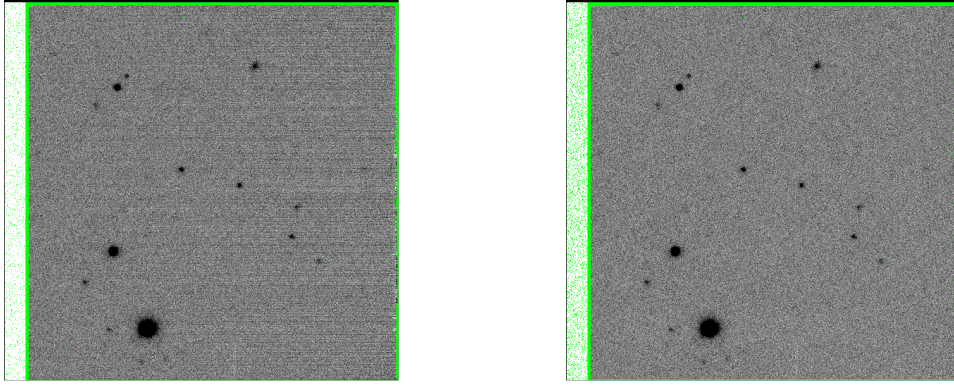


Fig. 8.— Example of the PATTERN.ROW correction on exposure o5379g0103o OTA57 cell xy00 (i_{P1} filter 45s). The left panel shows the cell with all appropriate detrending except the PATTERN.ROW, and the right shows the same cell with PATTERN.ROW applied. The correction reduces the correlated noise on the right side, which is most distant from the read out amplifier. There is a slight over subtraction along the rows near the bright star.

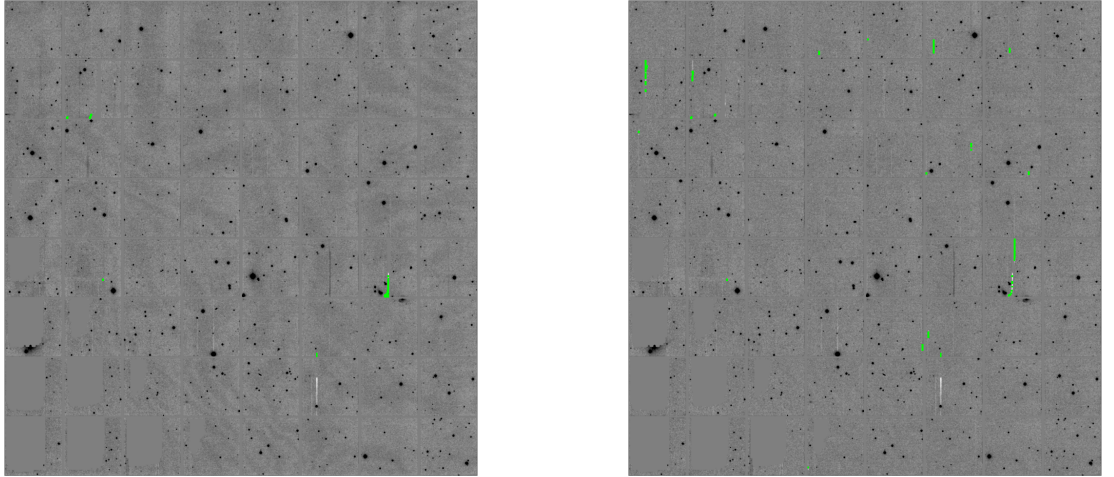


Fig. 9.— Example of the y_{P1} filter fringe pattern on exposure o5220g0025o OTA53 (y_{P1} filter 30s). The left panel shows the OTA mosaic with all detrending except the fringe correction, while the right shows the same including the fringe correction. Both images have been smoothed with a Gaussian with $\sigma = 3$ pixels to highlight the faint and large scale fringe patterns.

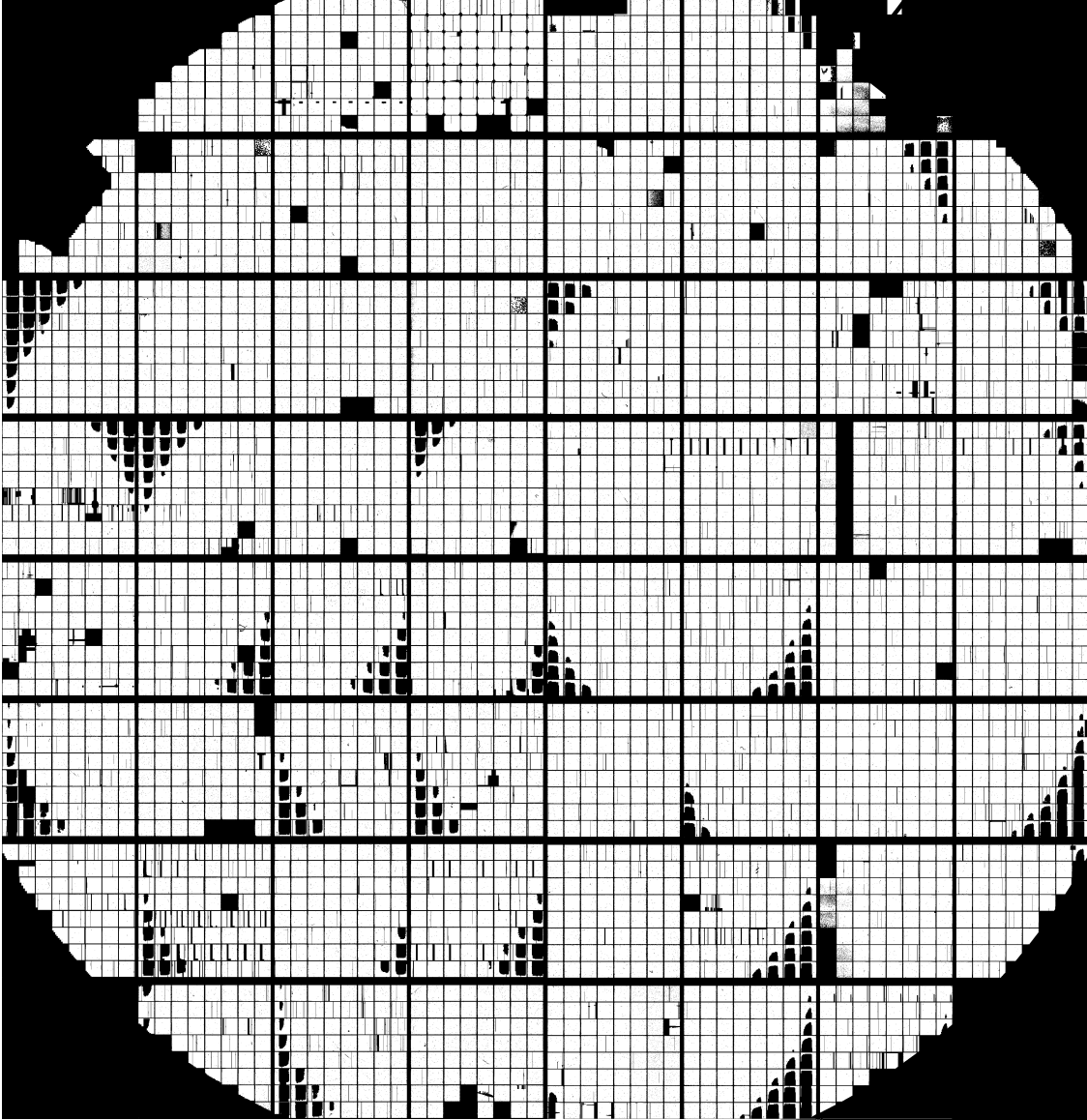


Fig. 10.— Image map of the GPC1 static mask. The CTE regions are clearly visible as roughly triangular patches covering the corners of some OTAs. Some entire cells are masked, including an entire column of cells on OTA14. Calcite cells remove large areas from OTA17 AND OTA76.

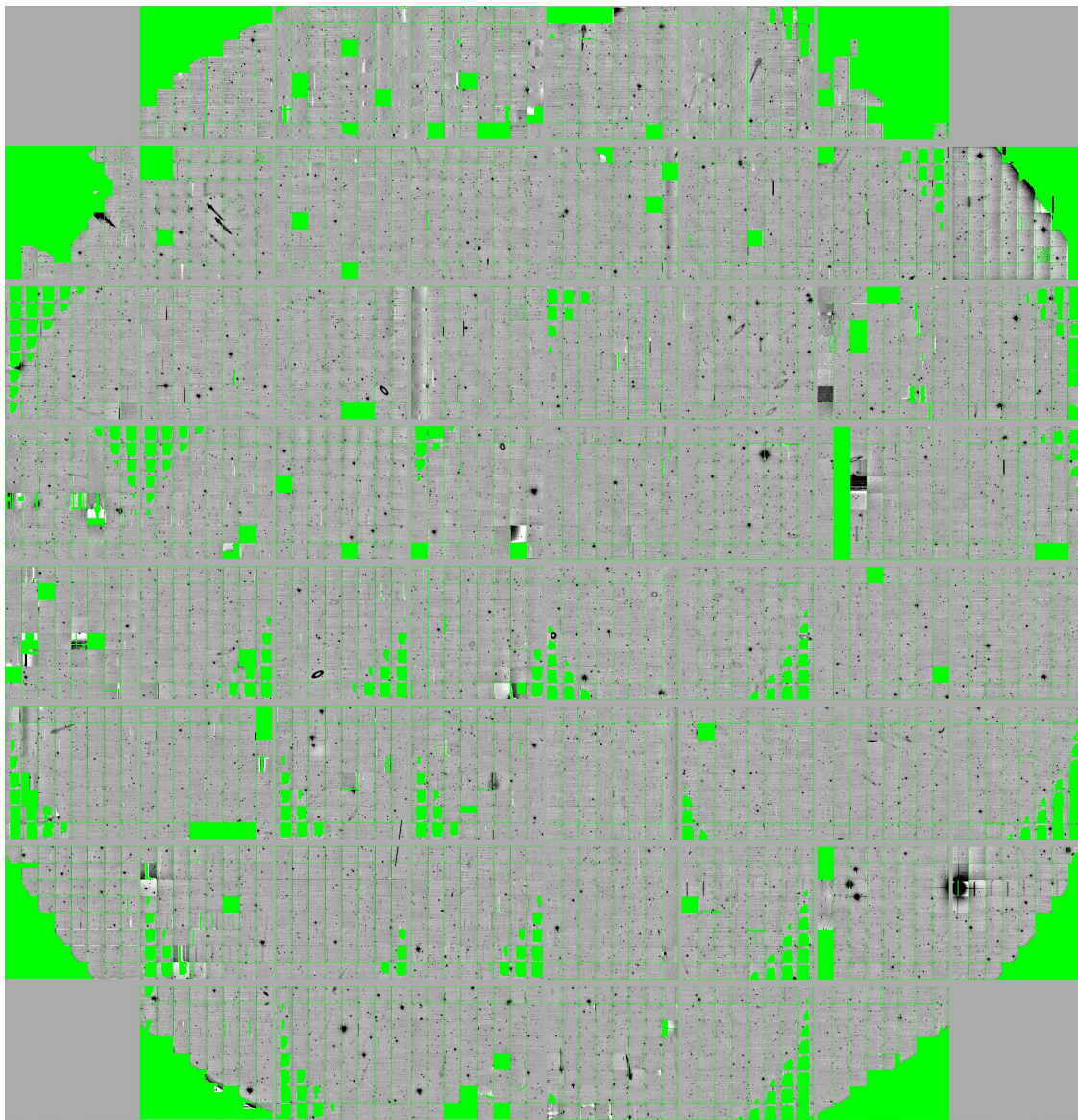


Fig. 11.— Example of the full GPC1 field of view illustrating the sources and destinations of optical ghosts on exposure o5677g0123o (2011-04-26, 43s g_{P1} filter). The bright stars on OTA33 and OTA44 result in nearly circular ghosts on the opposite OTA. In contrast, the trio of stars on OTA11 result in very elongated ghosts on OTA66.

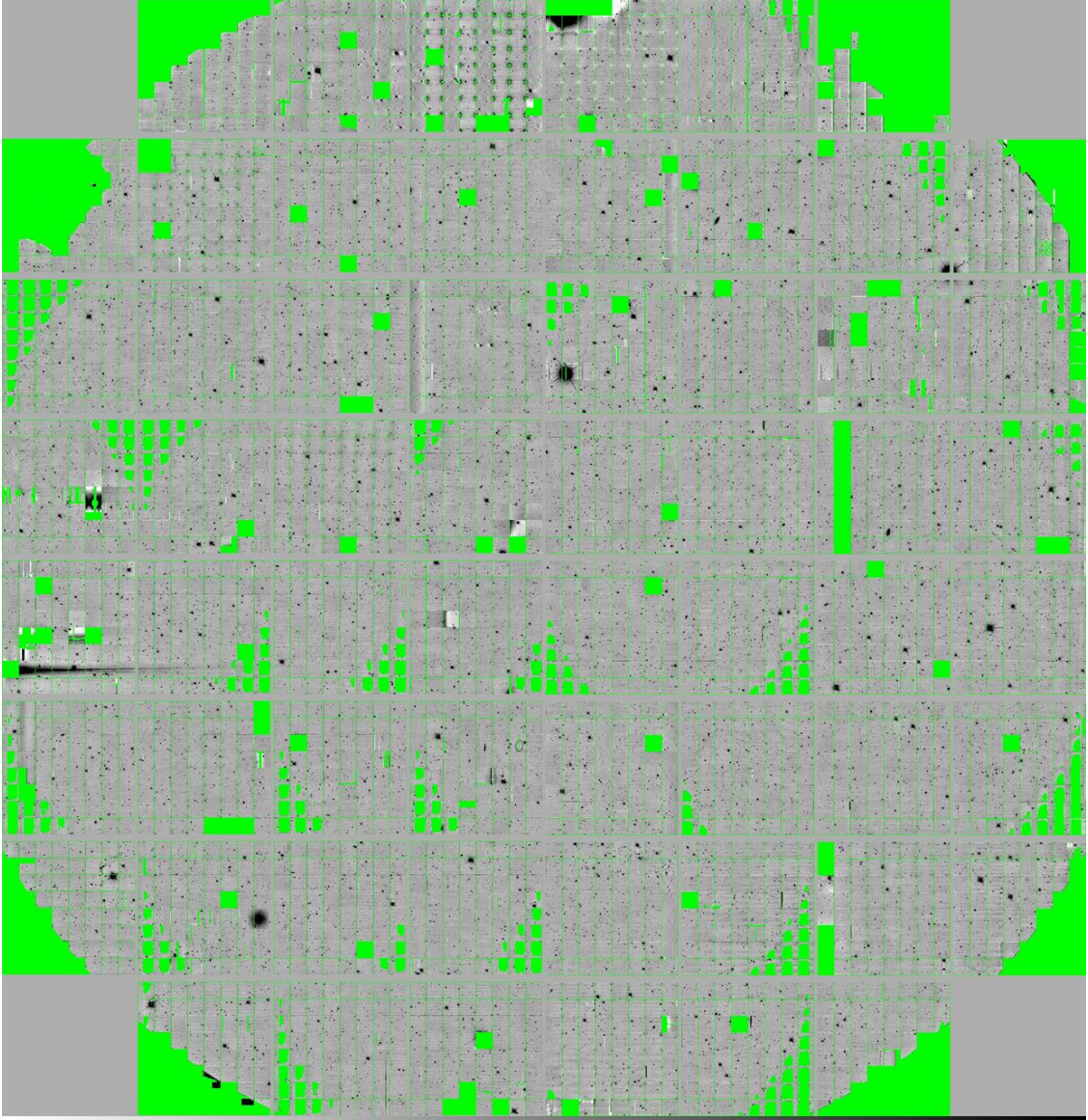


Fig. 12.— Example of a glint on exposure o5379g0103o (2010-07-02, 45s i_{P1} filter). The source star out of the field of view creates a long reflection that extends through OTA73 and OTA63.

and width $W = 8 + (L - 200) * 0.01$, with negative values indicating no mask is constructed, as the source is likely too faint to produce the feature. These spikes are dependent on the camera rotation, and are oriented at $\theta = n * \frac{\pi}{2} - \text{ROTANGLE} + 0.798$, based on the header keyword.

The cores of stars that are saturated are masked as well, with a circular mask radius $r = 10.15 * (-15 - m_{\text{instrumental}})$. An example of a saturated star, with the masked regions for the diffraction spikes and core saturation highlighted, is shown in Figure 13.

2.9.3. Masking Fraction

For the full field of view that falls on the sixty OTAs, 14.7% of all pixels are masked. The large fraction of this masking is due to regions that fall within the vignetted region. Defining the diameter of the unvignetted region to have be 3 degrees, and excluding pixels that fall beyond this point reduces the static masking fraction to 9.7%.

Unfortunately, due to the design of the OTAs and readout cells, a non-negligible fraction of the field of view falls onto an area that does not have a detector pixel. For a given OTA mosaicked to a 4846×4868 pixel image, the $64\,590 \times 598$ pixel readout cells cover 95.7% of the OTA area, providing an additional 4.3% masking in the unvignetted field of view due to the absence of a detector pixel.

For the inter-chip gap area loss, we use two field of view calculations to estimate the masking fraction. The reference field of view of GPC1 is 3 degrees, which at the nominal plate scale of 0.258 arcseconds per pixel, translates to a 20930 FPA pixel radius. Summing mask fractions from these three contributions within the unvignetted field of view results in an average of $\sim 20\%$ masking fraction across the field of view. Dynamic masking adds an additional 2 – 3% on average, with advisory burnttool masking contributing the largest single component. Table 7 contains estimates of the mask fraction in the GPC1 detector footprint by the sources of the masking for the 3 degree field of view, as well as for a larger 3.25 degree

Table 5. Optical Ghost Annulus Axis Length

Radial Order	Inner Major Axis	Inner Minor Axis	Outer Major Axis	Outer Minor Axis
r^0	3.926693e+01	5.287548e+01	7.928722e+01	1.314265e+02
r^1	5.325759e-03	-2.191669e-03	1.722181e-02	-2.627153e-03

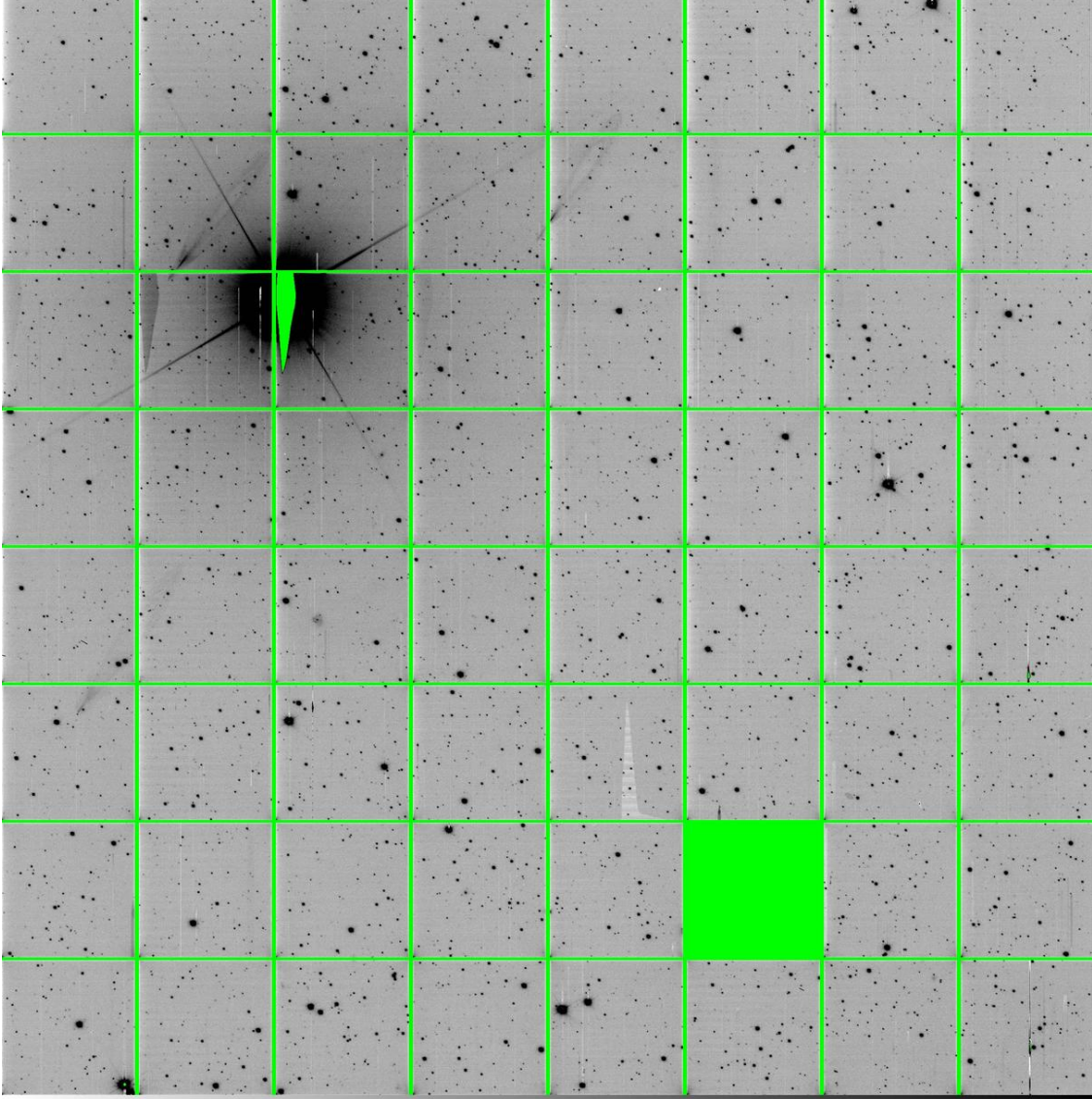


Fig. 13.— Example of saturated star, with diffraction spikes extending from the core on exposure o6802g0338o, OTA51 (2014-05-25, 45s g_{P1} filter).

field of view that allows addition unvignetted regions in the corners to contribute.

2.10. Background subtraction

Once all other detrending is done, the pixels from each cell are mosaicked into the full 4846×4868 pixel OTA image. A background model for the full OTA is then determined prior to the photometric analysis. The mosaicked image is subdivided into 800×800 pixel segments that define each pixel of the background model, with the segments centered on the image center, and overlapping adjacent subdivisions by 400 pixels. These overlaps help smooth the background model, as adjacent model pixels share input pixels.

From each subdivision, 10000 random unmasked pixels are drawn. In the case where the mask fraction is large (such as on OTAs near the edge of the field of view), and there are insufficient unmasked pixels to meet this criterion, all possible unmasked pixels are used instead. If this number is still small (less than 100 good pixels), the subdivision does not have a background model calculated, and instead, the value assigned to that model pixel is set as the average of the adjacent model pixels. This allows up to eight neighboring background values to be used to patch these bad pixels.

For the remaining subdivisions that have sufficient unmasked pixels for the background to be measured, the pixel values are used to calculate a set of robust statistics for the initial background guess. The minimum and maximum of the values are found, and checked to ensure that these are not the same value, which would indicate some problem with the input values. The values are then inserted into a histogram with 1000 bins between the minimum and maximum values, and again checked for issues with the inputs by ensuring that the

Table 6. Optical Ghost Magnitude Limits

Filter	m_{inst}
g_{P1}	-16.5
r_{P1}	-20.0
i_{P1}	-25.0
z_{P1}	-25.0
y_{P1}	-25.0
w_{P1}	-20.0

bin with the most input pixels does not contain more than half of the input values. In this case, the minimum and maximum do not constrain the true distribution of the input values well, and any values outside of the 20 bins closest to the bin with the peak are masked for future consideration. A cumulative distribution is then constructed from the histogram, which saves the computational cost of sorting all the input values. The bins containing the 50-percentile point, as well as the 15.8%, 84.1% ($\pm 1\sigma$), 30.8%, 69.1% ($\pm 0.5\sigma$), 2.2%, and 97.7% ($\pm 2\sigma$) points are identified in this cumulative histogram. These bins, and the two bins to either side are then linearly interpolated to identify the pixel value corresponding to these points in the distribution. The 50% point is set as the median of the pixel distribution, with the standard deviation of the distribution set as the median of the σ values calculated from the $0.5 * (\sigma_{+1} - \sigma_{-1})$, $\sigma_{+0.5} - \sigma_{-0.5}$, and $0.25 * (\sigma_{+2} - \sigma_{-2})$ differences. If this measured standard deviation is smaller than 3 times the bin size, then all points more than 25 bins away from the calculated median are masked, and the process is repeated until the bin size is sufficiently small to ensure that the distribution width is well sampled. Once this iterative process converges, or 20 iterations are run, the 25- and 75-percentile values are found by interpolating the 5 bins around the expected bin as well, and the count of the number of input values within this inner 50-percentile region, N_{50} is calculated.

These initial statistics are then used as the starting guesses for a second calculation of the background level that attempts to fit the distribution with a Gaussian. All pixels that were masked in the initial calculation are unmasked, and a histogram is again constructed of the values, with a bin size set to $\sigma_{guess} / (N_{50}/500)$. With this bin size, we expect that a bin at $\pm 2\sigma$ will have approximately 50 input points, which gives a Poissonian signal to noise estimate around 7. In the case where N_{50} is small (due to a poorly populated input image), this bin size is fixed to be no larger than the guess of the standard deviation. The endpoints of the histogram are clipped based on the input guesses, such that any input point with a value more than $5\sigma_{guess}$ away from the input mean are excluded from consideration.

Two second order polynomial fits are then performed to the logarithm of the histogram

Table 7. Mask Fraction by Mask Source

Mask Source	3 Degree FOV	3.25 Degree FOV
No pixel	4.44%	9.47%
Detector defect	6.37%	7.91%
CTE issue	2.62%	3.13%

counts set at the midpoint of each bin. The first fit considers the “lower half” of the distribution, under the assumption that deviations from a normal distribution are caused by real astrophysical sources that will be brighter than the true background level. From the bin with most pixel values, the lower bound is set by searching for the first bin from the peak that has fewer inputs than 25% of the peak. A similar search is performed for the upper bound, but with a criterion that the bin has fewer than 50% of the peak. On both sides of the peak, the bounds are adjusted to ensure that at least seven bins, equally distributed around the peak, are used. The second fit is symmetric, fitting both sides of the distribution out to the point where the bin contains fewer than 15% of the peak value. The same seven-bin constraint is used for this fit. The Gaussian mean and standard deviation are calculated from the polynomial coefficients, and the symmetric fit results are accepted unless the lower-half fit results in a smaller mean. This process is repeated again if the calculated standard deviation is not larger than 75% of the initial guess (suggesting an issue with the initial bin size).

With this two-stage calculation performed across all subdivisions of the mosaicked OTA image, and missing model pixels filled with the average of their neighbors, the final background model is stored on disk as a 13×13 image with header entries listing the binning used. The full scale background image is then constructed by bilinearly interpolating this binned model, and this is subtracted from the science image. Each object in the photometric catalog has a SKY and SKY_SIGMA value that is the evaluation of this model at the location of that object.

Although this background modeling process works well for most of the sky, astronomical sources that are large compared to the 800×800 pixel subdivisions can bias the calculated background level high, resulting in an oversubtraction near that object. The most common source that can cause this issue are large galaxies, which can have their own features modeled as being part of the background. For the specialized processing of M31, which covers an entire pointing of GPC1, the measured background was added back to the CHIP stage images, but this special processing was not used for the large scale 3II PV3 reduction.

3. GPC1 Detrend Construction

The various detrends for GPC1 are constructed in similar ways. A series of appropriate exposures is selected from the database, and processed with the `ppImage` program. This program is used for the CHIP stage processing as well, and is designed to do multiple image processing operations. The extent of this processing is dependent on the order in which the detrend to be constructed is applied to science data. In general, the input exposures to

the detrend have all prior stages of detrend processing applied. Table 8 summarizes stages applied for the detrends we construct.

Once the input data has been prepared, the **ppMerge** program is used to construct some sort of “average” of the inputs. This step need not be a mathematical average, but is used to combine the signal from the individual exposures into a single output product. Table 9 lists some of the properties of the process for the detrends, including how discrepant values are removed and the combination method used. The outputs from this step have the format of the detrend under construction, and after construction, are applied to the processed input data. This creates a set of residual files that are checked to determine if the newly created detrend correctly removes the detector dependent signal.

This process of detrend construction and testing can be iterated, with individual exposures excluded if they are found to be contaminating the output. If the final detrend has sufficiently small residuals, then the iterations are stopped and the detrend is finalized by selecting the date range to which it applies. This allows subsequent science processing to select the detrends needed based on the observation date. Table 10 lists the set of detrends used in the PV3 processing.

Table 8. Detrend Construction Processing

Detrend Type	Overscan Subtracted	Nonlinearity Correction	Dark Subtracted	Flat Applied
LINEARITY	Y			
DARKMASK	Y	Y	Y	
FLATMASK	Y	Y	Y	Y
CTEMASK	Y	Y	Y	Y
DARK	Y	Y		
NOISEMAP	Y	Y		
FLAT	Y	Y	Y	
FRINGE	Y	Y	Y	Y

Table 9. Detrend Merge Options

Detrend Type	Iterations	Threshold	Additional Clipping	Combination Method
DARKMASK	3	8σ		Mask if $> 10\%$ rejected
FLATMASK	3	3σ		Mask if $> 10\%$ rejected
CTEMASK	2	2σ		Clipped mean; mask if $\sigma^2/\langle I \rangle < 0.5$
DARK	2	3σ		Clipped mean
NOISEMAP	2	3σ		Mean
FLAT	1	3σ	Top 30%; Bottom 10%	Mean
FRINGE	2	3σ		Clipped mean

Table 10. PV3 Detrends

Detrend Type	Detrend ID	Start Date	End Date	Note
LINEARITY	421	2009-01-01 00:00:00		
MASK	945	2009-01-01 00:00:00		
	946	2009-12-09 00:00:00		
	947	2010-01-01 00:00:00		
	948	2011-01-06 00:00:00		
	949	2011-03-09 00:00:00	2011-03-10 23:59:59	
	950	2011-08-02 00:00:00		
	1072	2015-12-17 00:00:00		Update OTA62 mask
DARK	223	2009-01-01 00:00:00	2009-12-09 00:00:00	
	229	2009-12-09 00:00:00		
	863	2010-01-23 00:00:00	2011-05-01 00:00:00	A-mode
	864	2011-05-01 00:00:00	2011-08-01 00:00:00	
	865	2011-08-01 00:00:00	2011-11-01 00:00:00	
	866	2011-11-01 00:00:00	2019-04-01 00:00:00	
	869-935	2010-01-25 00:00:00 ^a	2011-04-25 23:59:59 ^a	B-mode
VIDEODARK	976	2009-01-01 00:00:00	2009-12-09 00:00:00	
	977	2009-12-09 00:00:00	2010-01-23 00:00:00	
	978	2010-01-23 00:00:00	2011-05-01 00:00:00	A-mode
	979	2011-05-01 00:00:00	2011-08-01 00:00:00	
	980	2011-08-01 00:00:00	2011-11-01 00:00:00	
	981	2011-11-01 00:00:00	2019-04-01 00:00:00	
	982-1048	2010-01-25 00:00:00 ^a	2011-04-25 23:59:59 ^a	B-mode
	1049	2010-09-12 00:00:00	2011-05-01 00:00:00	A-mode with OTA47fix
NOISEMAP	963	2008-01-01 00:00:00	2010-09-01 00:00:00	
	964	2010-09-01 00:00:00	2011-05-01 00:00:00	
	965	2011-05-01 00:00:00		
FLAT	300	2009-12-09 00:00:00		g_{P1} filter
	301	2009-12-09 00:00:00		r_{P1} filter
	302	2009-12-09 00:00:00		i_{P1} filter
	303	2009-12-09 00:00:00		z_{P1} filter
	304	2009-12-09 00:00:00		y_{P1} filter

4. Warping

To provide a consistent and uniform set of images for co-added image stacking and differences, the individual mosaicked OTA images are projected onto a common set of tangent plane projected regions called projection cells. These projection cells are 4×4 degree fields spaced onto a set of centers that fully cover the sky. They are arranged into rings of constant declination, and allowed to overlap as $|\delta|$ increases. Each projection cell is further subdivided into 10×10 sky cells with fixed $0.25''$ resolution pixels, and constant overlap regions between adjacent skycells of $60''$. These skycells are the main image unit used for processing image data beyond the initial chip stage. The coordinate system used for these images matches the parity of the sky, with north in the positive y direction and east to the negative x direction.

After the detrending and photometry, the detection catalog for the full camera is fit to the reference catalog, producing third-order astrometric solutions that map the detector focal plane to the sky, and map the individual OTA pixels to the detector focal plane. This solution is then used to determine which skycells the exposure OTAs overlap.

For each output skycell, all overlapping OTAs and the calibrated catalog are read into the `pswarp` program. Each input image is examined in order, and the same transformation performed. This transformation breaks the output warp image into 128×128 pixel grid boxes. Each grid box has a locally linear map calculated that converts the output warp image coordinates to the input chip image coordinates. By doing the transformation in this direction, each output pixel has a unique sampling position on the input image (although it may be off the image frame and therefore not populated), preventing gaps in the output image due to the spacing of the input pixels.

With the locally linear grid defined, Lanczos interpolation with filter size parameter

Table 10—Continued

Detrend Type	Detrend ID	Start Date	End Date	Note
	305	2009-12-09 00:00:00		w_{P1} filter
FRINGE	296	2009-12-09 00:00:00		
ASTROM	1064	2008-05-06 00:00:00		

^aThese dates mark the beginning and ending of the two-mode dark models, between which multiple dates use the B-mode dark.

$a = 3$ on the input image is used to determine the values to assign to the output pixel location. The output locations are shifted by 0.5 pixels to let the interpolation select the value that would be assigned to the center of the output pixel. This process is repeated for all grid boxes, for all input images, and for each output image product: the science image, the variance, and the mask. The image values are scaled by the absolute value of the Jacobian determinant of the transformation. This corrects the pixel values for the possible change in pixel area due to the transformation. Similarly, the variance image is scaled by the square of this value, again to correctly account for the pixel area change.

As the interpolation constructs the output pixels from more than one input pixel, there is a covariance term that must be included. For each locally linear grid box, the covariance is calculated from the kernel in the center of the 128 pixel range. Once the image has been fully populated, this set of individual covariance matrices is averaged to create the final covariance for the full image.

An output catalog is also constructed from the full exposure input catalog, including only those objects that fall on the new warped image. These detections are transformed to match the new image location, and to scale the position errors based on the new orientation.

The output image also contains header keywords SRC_0000, SEC_0000, MPX_0000, and MPY_0000 that contain the mappings from the warped pixel space to the input image. The SRC keyword lists the input OTA name, and the SEC keyword lists the image section corresponding to the locally linear grid box. The MPX and MPY contain the transformation parameters for the locally linear grid. These parameters are stored in a string listing the reference position in the chip coordinate frame, the slope of the relation in the warp x axis, and the slope of the relation in the warp y axis. From these keywords, any position in the warp can be mapped back to the location in any of the input OTA images.

5. Stacking

Once individual exposures have been warped onto a common projection system, they can then be combined pixel-by-pixel regardless of their original orientation. Creating a stacked image by co-adding the individual warps increases the signal to noise, allowing for the detection of objects that would not be sufficiently significant to be measured from a single image. Creating this stack also allows a complete image to be constructed that does not have regions masked due to the gaps between cells and OTAs. This fully populated static sky image can also be used as a template for subtraction to find transient sources.

The stacked image is comprised of all warp frames for a given skycell in a single filter.

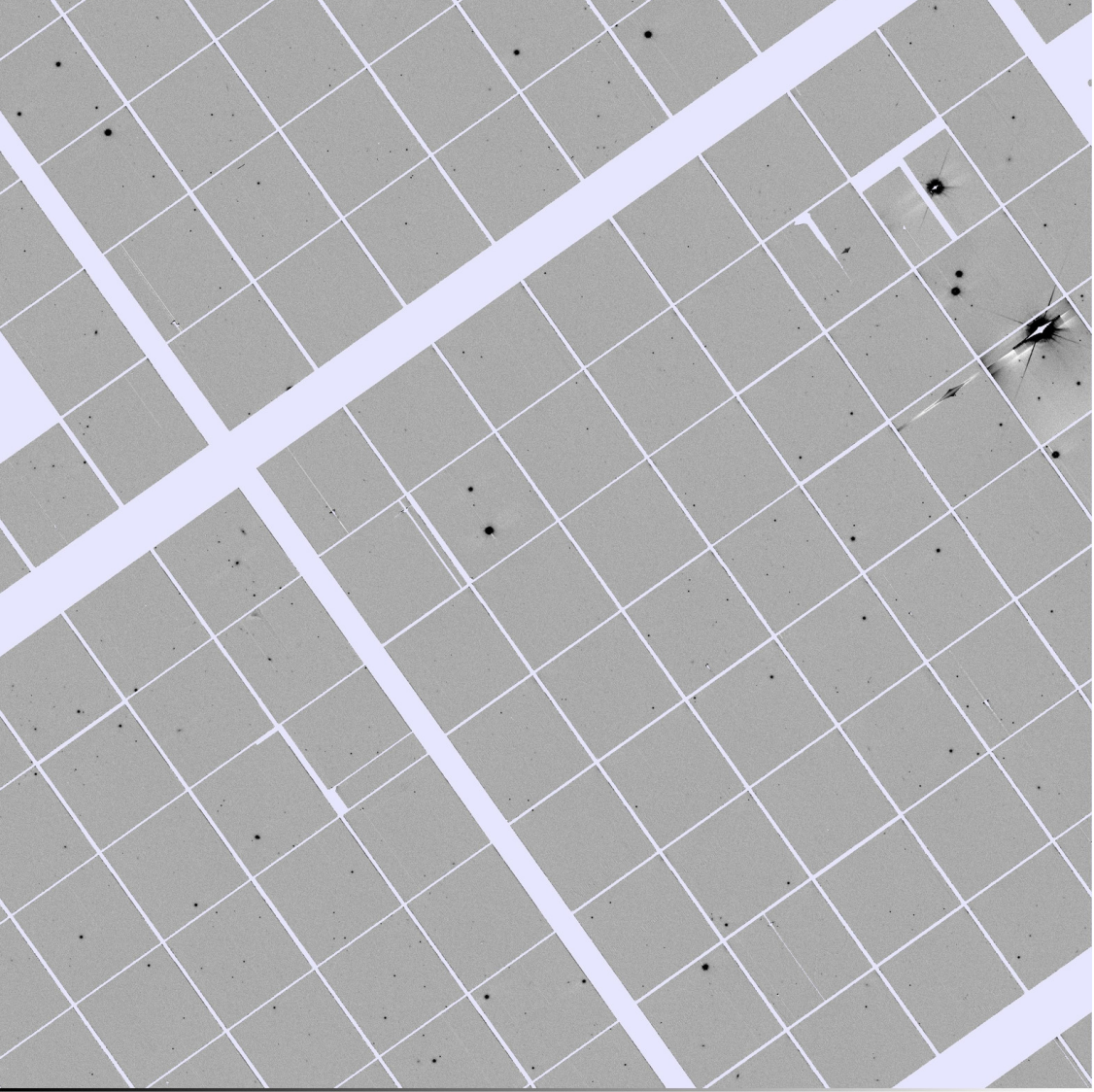


Fig. 14.— Example of the warp image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ for exposure o4985g0073o, (2009-06-03, 30s z_{P1} filter). The data from six OTAs contribute to this image, although they are all truncated by the skycell boundaries. This skycell image is aligned such that north points to the top of the image, and east to the left. The contributing OTAs are from the right half of the detector, with OTA24 contributing the most pixels, and originally have the positive y axis pointing to the southwest in this warped image, with the positive x axis to the northwest.

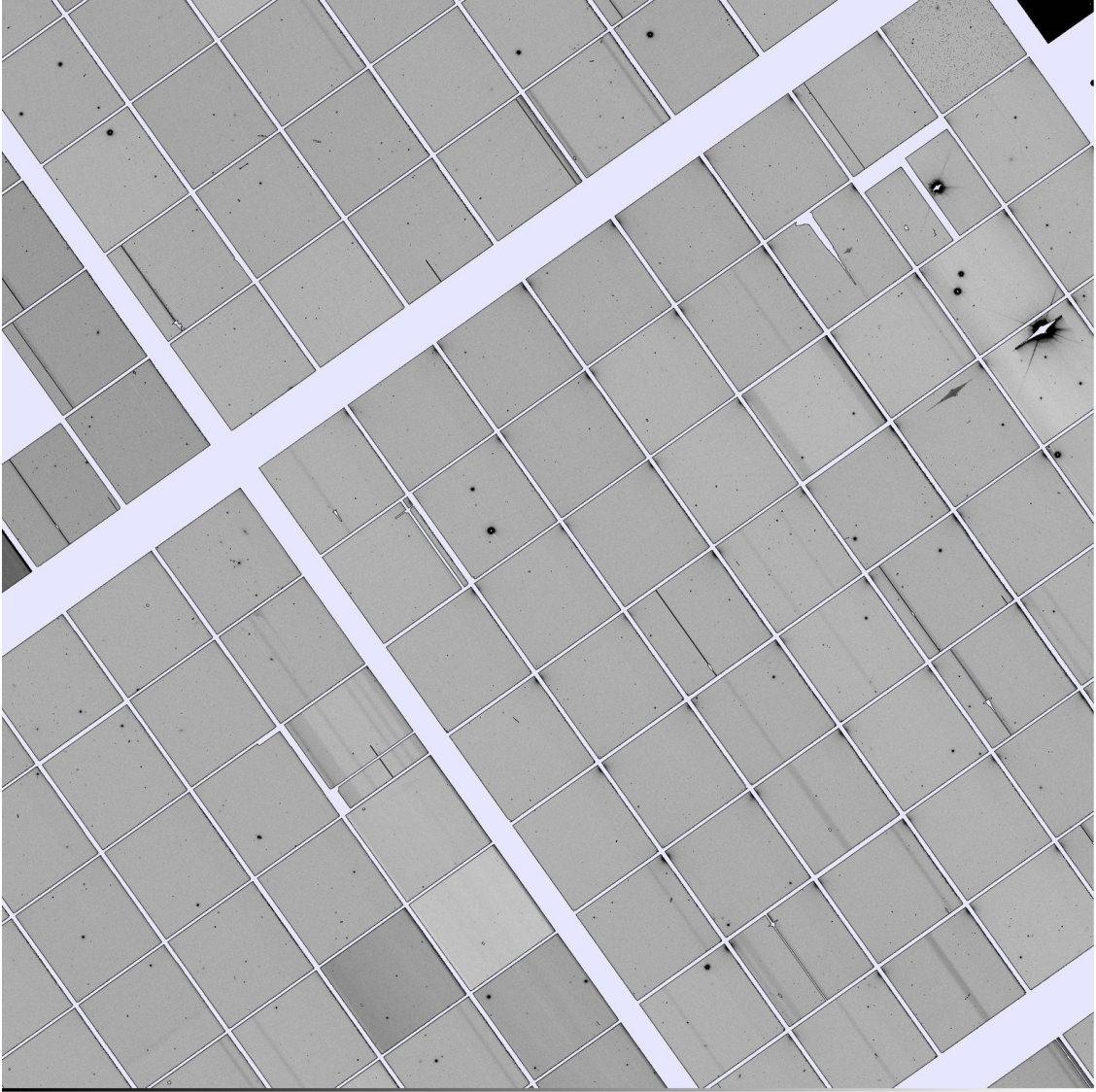


Fig. 15.— Example of the warp variance image for skycell skycell.2047.005 of exposure o4985g0073o, the same as in Figure 14. This variance map retains information about the higher flux levels that were found in burnttool corrected persistence trails, which appear here as streaks along the original OTA y axis. The amplifier glows that are corrected in the dark model are also more visible in the corners of the cells in OTA24. As both of these effects are corrected in the science image, there are no significant features visible there.

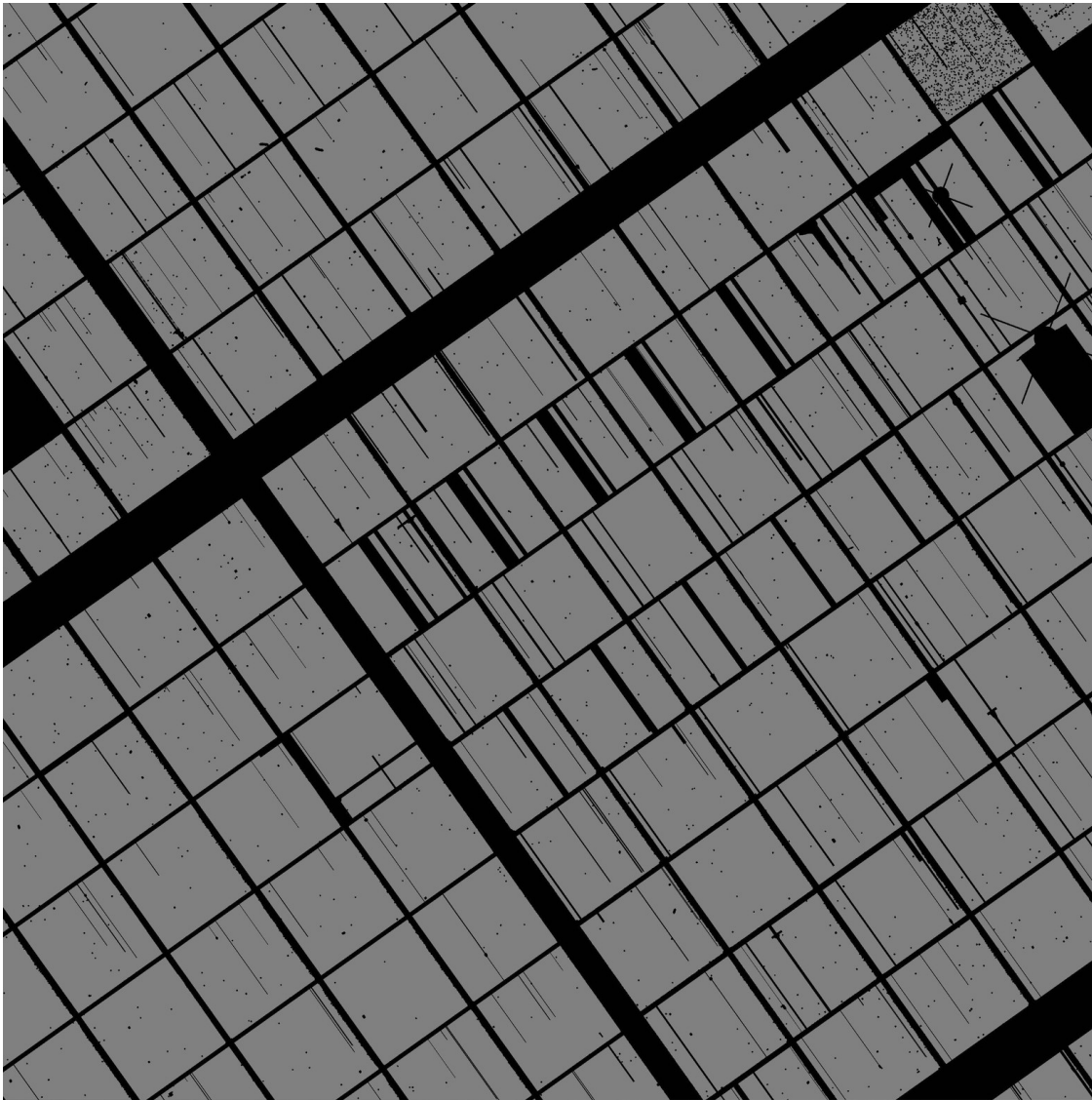


Fig. 16.— Example of the warp mask image for skycell skycell.2047.005 of exposure o4985g0073o, the same as in Figure 14. This mask image shows the many small defects removed from the image, along with larger advisory trails on corrected burntout trails. The saturated cores of the bright stars are also masked, along with the diffraction spikes found on these stars. In addition OTA24 shows the precautionary crosstalk bleed masks for the two brightest stars applied to all cells within the same row.

The source catalogs and image components are loaded into the `ppStack` program to prepare the inputs and stack the frames.

Once all files are ingested, the first step is to measure the size and shapes of the input image PSFs. We exclude images that have a PSF FWHM greater than 10 pixels (2.5 arcseconds), as those images have the seeing far worse than average, and would degrade the final output stack. For the PV3 3II survey, this size represents a PSF larger than the 97th percentile in all filters. A target PSF for the stack is constructed by finding the maximum envelope of all input PSFs, which sets the target PSF to the largest value among the input PSFs for a given position from the peak. This PSF is then circularized to ensure azimuthal symmetry, which prevents deconvolution of any of the input images when matched to the target.

The input images also need to have their fluxes normalized to prevent differences in seeing and sky transparency from causing discrepancies during pixel rejection. From the reference catalog calibrated input catalogs, we have the instrumental magnitudes of all sources, along with the airmass, image exposure time, and zeropoint. All output stacks are calibrated to a zeropoint of 25.0 in all filters, and to have an airmass of 1.0. The output exposure time is set to the sum of the input exposure times, regardless of if those inputs are rejected later in the combination process. We can determine the relative transparency for each input image by comparing the magnitudes of matched sources between the different images. Each image then has a normalization factor defined, equal to $\text{norm}_{\text{input}} = (ZP_{\text{input}} - ZP_{\text{target}}) - \text{transparency}_{\text{input}} - 2.5 * \log_{10}(t_{\text{target}}/t_{\text{input}}) - F_{\text{airmass}} * (\text{airmass}_{\text{input}} - \text{airmass}_{\text{target}})$. For the PV3 processing, the airmass factor F_{airmass} was set to zero, such that all flux differences from differing exposure airmasses are assumed to be included in the zeropoint and transparency values.

The zeropoint calibration performed here uses the calibration of the individual input exposures against the reference catalog. Upon the conclusion of the survey, the entire set of detection catalogs is further re-calibrated in the “ubercal” process (Schlafly et al. 2012). This produces a more consistent calibration of each exposure across the entire region of the sky imaged. This further calibration is not available at the time of stacking, and so there may be small residuals in the transparency values as a result of this Magnier et al. (2017).

With the flux normalization factors and target PSF chosen, the convolution kernels can be calculated for each image. ISIS kernels (Alard & Lupton 1998) are used with FWHM values of 1.5, 3.0, and 6.0 pixels and polynomial orders of 6, 4, and 2. Regions around the sources identified in the input images are extracted, convolved with the kernel, and the residual with the target PSF used to update the parameters of the kernel via least squares optimization. Stamps that significantly deviate are rejected, but as the squared residual

difference will increase with increasing source flux. To mitigate this effect, a parabola is fit to the distribution of squared residuals as a function of source flux. Stamps that deviate from this fit by more than 2.5σ are rejected, and not used on further kernel fit iterations. This process is repeated twice, and the final convolution kernel is returned.

This convolution may change the image flux scaling, so a normalization factor is used to correct this. This normalization factor is equal to the ratio of $10^{-0.4\text{norm}_{input}}$ to the sum of the kernel. The image is multiplied by this factor, and the variance by the square of it, scaling all inputs to the common zeropoint.

Once the convolution kernels are defined for each image, they are used to convolve the image to match the target PSF. Any input image that has a kernel match χ^2 value greater than 4.0σ larger than the median value is rejected from the stack. Each image also has a weight assigned, based on the image variance after convolution. A full image weight is then calculated for each input, with the weight, W_{input} is equal to the inverse of the median of the image variance multiplied by the peak of the image covariance (due to the warping process).

Following the convolution, an initial stack is constructed. For a given pixel coordinate, the values at that coordinate are extracted from all input images. Images that have a suspect mask bit (including the SUSPECT, BURNTOL, SPIKE, STREAK, STARCORE, and CONV.POOR bit values) are appended to a suspect pixel list for preferential exclusion. Following this, the pixel values are combined and tested to attempt to identify discrepant input values that should be excluded.

If only a single input is available, the initial stack contains the value from that single input. If there are only two inputs, the average of the two is used. These cases should occur only rarely in the 3I survey, as there are many input exposures that overlap each point on the sky. For the more common case of three or more inputs, a weighted average from the inputs is used, with the weight for each image as defined above used for all pixels from that input image. This weight is used for both the image and the exposure weighted image:

$$\text{Stack}_{\text{value}} = \sum_i (\text{value}_{\text{input}} * W_{\text{input}}) / \sum_{\text{inputs}} (W_{\text{input}}) \quad (1)$$

$$\text{Stack}_{\text{expweight}} = \sum_i (\text{exptime}_{\text{input}} * W_{\text{input}}) / \sum_{\text{inputs}} (W_{\text{input}}) \quad (2)$$

$$(3)$$

The pixel exposure time is simply the sum of the input exposure time values, and the output variance is

$$\text{Stack}_{\text{variance}} = 1 / \sum_i (1 / \sigma_{\text{input}}^2) \quad (4)$$

The output mask value is taken to be zero (no masked bits), unless there were no valid inputs, in which case the BLANK mask bit is set.

Due to the various non-astronomical ghosts that can occur on GPC1, and the fact that they may not be fully masked to ensure all bad pixels are removed, it is expected that some of the inputs for a given stack pixel are not in agreement with the others. In general, there is the population of input pixel values around the correct astronomical level, as well as possible populations at lower pixel value (such as due to an over-subtracted burnt tool trail) and at higher pixel values (such as that caused by an incompletely masked optical ghost). Due to the observation strategy to image a given field twice to allow for warp-warp difference images to be constructed to identify transient detections, higher pixel values that come from sources like optical ghosts that depend on the telescope pointing will come in pairs as well. The higher pixel value contaminants are also potentially problematic as they may appear to be real sources, prompting photometry to be performed on false objects. Because of the expectation that there are more bright contaminants than faint ones, there is a slight preference to reject higher pixel values than lower pixel values.

Following the initial combination, a “testing” loop iterates in an attempt to identify outlier points. Again, if only one input is available, that input is accepted. If there are two inputs, A and B , then a check is made to see if $(0.5 * (\text{value}_A - \text{value}_B))^2 > 16 * (\sigma_A^2 + \sigma_B^2 + (0.1 * \text{value}_A)^2 + (0.1 * \text{value}_B)^2)$, such that the deviation of the inputs from their mean position is greater than four times the sum of their measured uncertainties and a 10% systematic error term. If this is the case, neither input is trusted, and both are flagged for rejection.

If the number of inputs is larger than 6, then a Gaussian mixture model analysis is run on the inputs to fit two sub populations, and determine if the likelihood that the distribution is best described by a uni-modal model. If this probability is less than 5%, then the mean is taken from the bimodal sub population with the largest fraction of inputs, as this should exclude any sub population comprised of high pixel value outliers.

If this is not the case, and the distribution is likely unimodal, or if there are insufficient inputs for this mixture model analysis, the input values are passed to an Olympic weighted mean calculation. We reject 20% of the number of inputs through this process. The number of bad inputs is set to $N_{\text{bad}} = 0.2 * N_{\text{input}} + 0.5$, with the 0.5 term ensuring at least one input is rejected. This number is further separated into the number of low values to exclude $N_{\text{low}} =$

$N_{\text{bad}}/2$, which will default to zero if there are few inputs, and $N_{\text{high}} = N_{\text{input}} + N_{\text{low}} - N_{\text{bad}}$. After sorting the input values to determine which values fall into the low and high groups, the remaining input values are used in a weighted mean using the image weights above.

A systematic variance term is necessary to correctly scale how discrepant points can be from the ensemble mean. If the mixture model analysis was run, the Gaussian sigma from the largest sub population is squared and used. If this is not available, a 10% systematic error on the input values is used. Each point then has a limit calculated using a 4σ rejection

$$\text{limit}_{\text{mixture model}} = 4^2 * (\sigma_{\text{input}}^2 + \sigma_{\text{mixture model}}^2) \quad (5)$$

$$\text{limit}_{\text{default}} = 4^2 * (\sigma_{\text{input}}^2 + (0.1 * \text{value}_{\text{input}})^2) \quad (6)$$

Each input pixel is then compared against this limit, and the most discrepant pixel that has $(\text{value}_{\text{input}} - \text{mean})^2$ exceeding this limit is identified. If there are suspect pixels in the set, those pixels are marked for rejection, otherwise this worst pixel is marked for rejection. Following this, the combine and test loop is repeated for until no more pixels are rejected, up to a maximum number of iterations equal to 50% of the number of inputs.

With the initial list of rejected pixels generated, a rejection mask is made for the input warp by constructing an empty image that has the rejected pixels from that input set to a value of 1.0. This image is then convolved with a 5 pixel FWHM zeroth-order ISIS kernel. Any pixels that are above the threshold of 0.5 after this mask convolution are marked as bad and will be rejected in the final combination. If more than 10% of all pixels from an input image are rejected, then the entire image is rejected as it likely has some systematic issue.

Finally, a second pass at rejecting pixels is conducted, by growing the current list to include pixels that are neighbors to many rejected pixels. The ISIS kernel used in the previous step is again used to determine the largest square box that contains under the limit of $0.25 * \sum_{x,y} \text{kernel}^2$. This square box is then convolved with the rejected pixel mask to reject the neighboring pixels. This final list of rejected pixels is passed to the final combination, which creates the final stack values from the weighted mean of the non-rejected pixels. Six total images are constructed for this final stack: the image, its variance, a mask, a map of the exposure time per pixel, that exposure time map weighted by the input image weight, and a map of the number of inputs per pixel.

These convolved stack products are not retained, as the convolution reduces the resolution of the final image. Instead, we apply the normalizations and rejected pixel maps generated from the convolved stack process to the original unconvolved input images. This produces an unconvolved stack that has the optimum image quality possible from the input

images. Not convolving does mean that the PSF shape changes across the image, as the different PSF widths of the input images print through in the different regions to which they have contributed.

Due to the expected large range of data values in the final stacked image, saving them as compressed 16-bit integer images with linear BSCALE and BZERO scaling values is likely to offer poor reconstructions of the stacked image. This will lead either to truncation of the extrema of the image, or quantized values that are poorly spaced for the image histogram. Saving the images as 32-bit floating point values would alleviate this quantization issue, at the cost of a large increase in the disk space required for the stacked images.

Transforming the data prior to writing to disk by taking the logarithm of the pixel values can resolve this, with the complication that all data values must first be made positive, which then sets the highest quantization sampling near the lowest values in the image. Following techniques used by SDSS (York et al. 2000), we have instead opted to use the inverse hyperbolic sine function to transform the data. The domain of this function allows any input value to be converted. In addition, the quantization sampling can be tuned by placing the zero of the inverse hyperbolic sine function at a value where the highest sampling is desired.

Formally, prior to being written to disk, the pixel values are transformed by $C = \alpha \operatorname{asinh}\left(\frac{L - \text{BOFFSET}}{2.0 \cdot \text{BSOFTEN}}\right)$, where L are the linear input pixel values, C the transformed values, $\alpha = 2.5 \log_{10}(e)$. BOFFSET centers the transformed values, and the mean of the linear input pixel values is used. BSOFTEN controls the stretch of the transformation, and is set to $\sqrt{\alpha} \sigma_L$. These parameters are saved to the output image header. The image is then passed to the standard BSCALE and BZERO calculation and saved to disk.

To reverse this process (on subsequent reads of the image, for example in warp-stack difference calculations), the BOFFSET and BSOFTEN parameters are read from the header and the transformation inverted, such that: $L = \text{BOFFSET} + \text{BSOFTEN} \cdot (\exp(C/\alpha) - \exp(-C/\alpha))$.

6. Difference Images

Constructing difference images is essentially the same as that used in the stacking process. An image is chosen as a template, another image as the input, and after matching sources to determine the scaling and transparency, convolution kernels are defined that are used to convolve one or both of the images to a target PSF. The images are then subtracted, and as they should now share a common PSF, static sources are largely subtracted

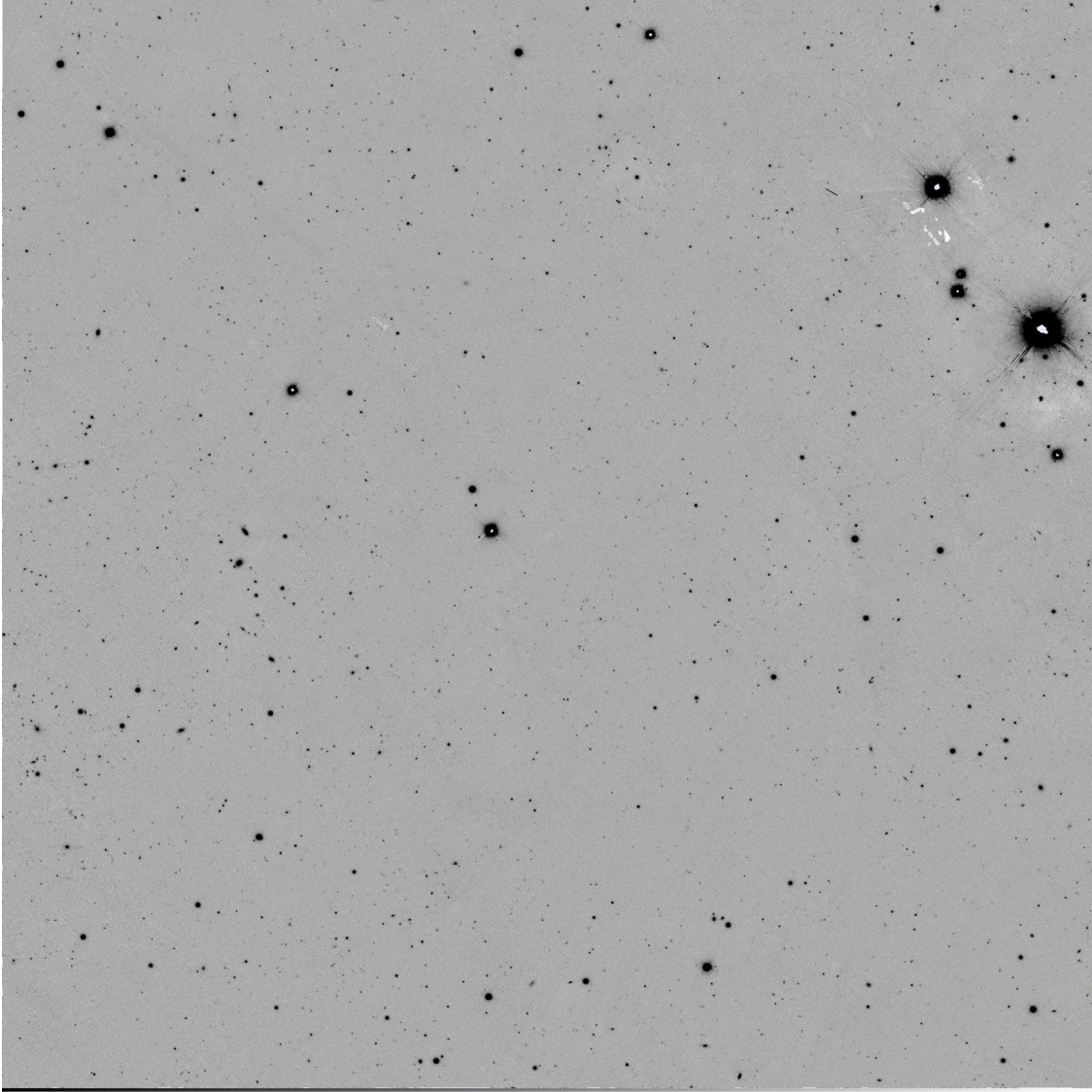


Fig. 17.— Example of the stack image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ in the z_{P1} filter, stack_id 3775944. This stack includes 25 input images, including o4985g0073o the warp image in Figure 14, and has a combined exposure time of 870s. Combining such a large number of input images removes the inter-cell and inter-chip gaps, providing a fully populated image. In addition, the combined signal allows many more faint objects to be found than were visible on the single frame warp image.

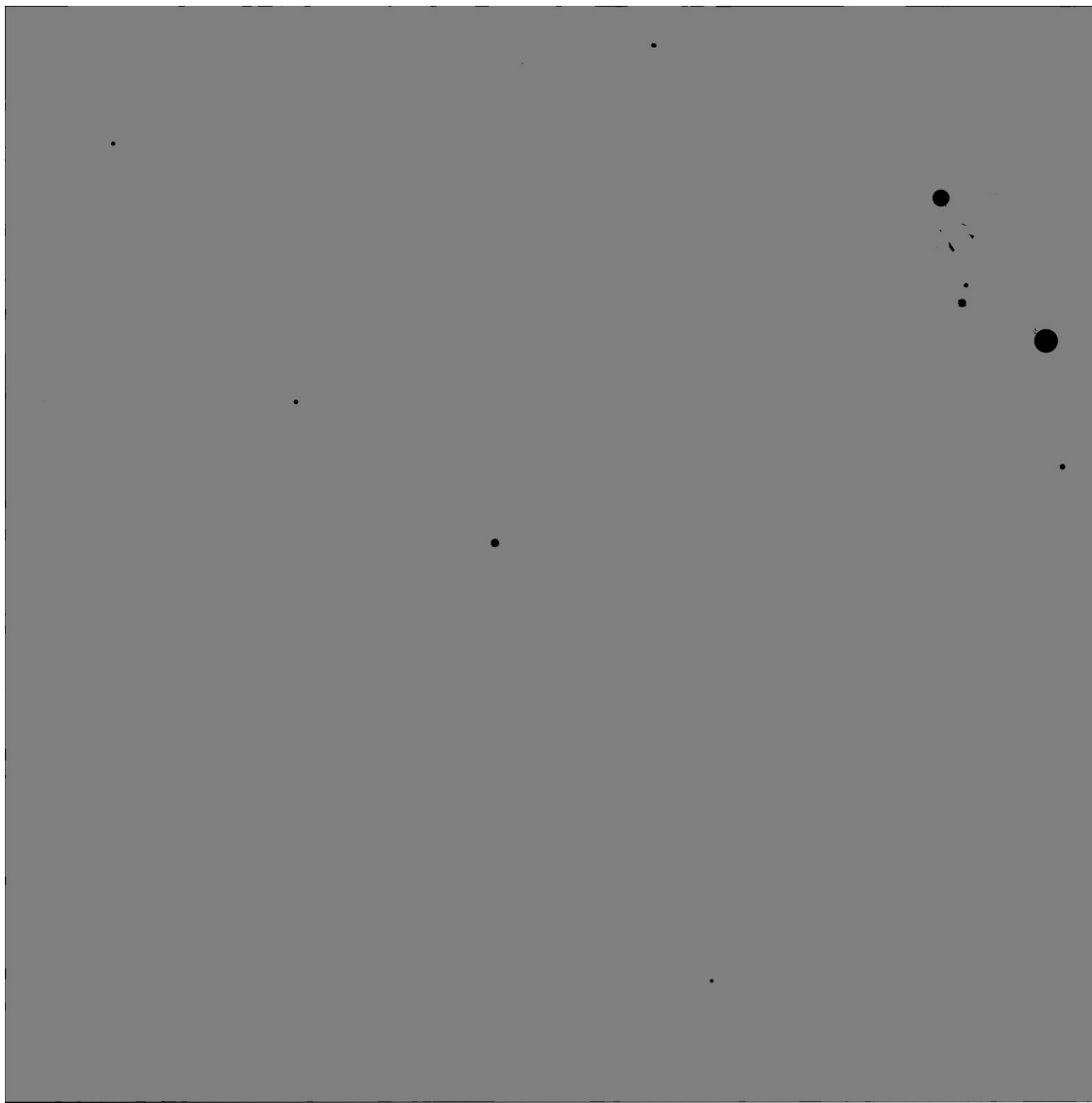


Fig. 18.— Example of the stack mask image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ in the z_{P1} filter, stack_id 3775944. The entire frame is largely unmasked after combining inputs, with the only remaining masks falling on the cores of bright stars, and in small regions around the brightest objects where the overlapping of diffraction spike masks have removed all inputs.

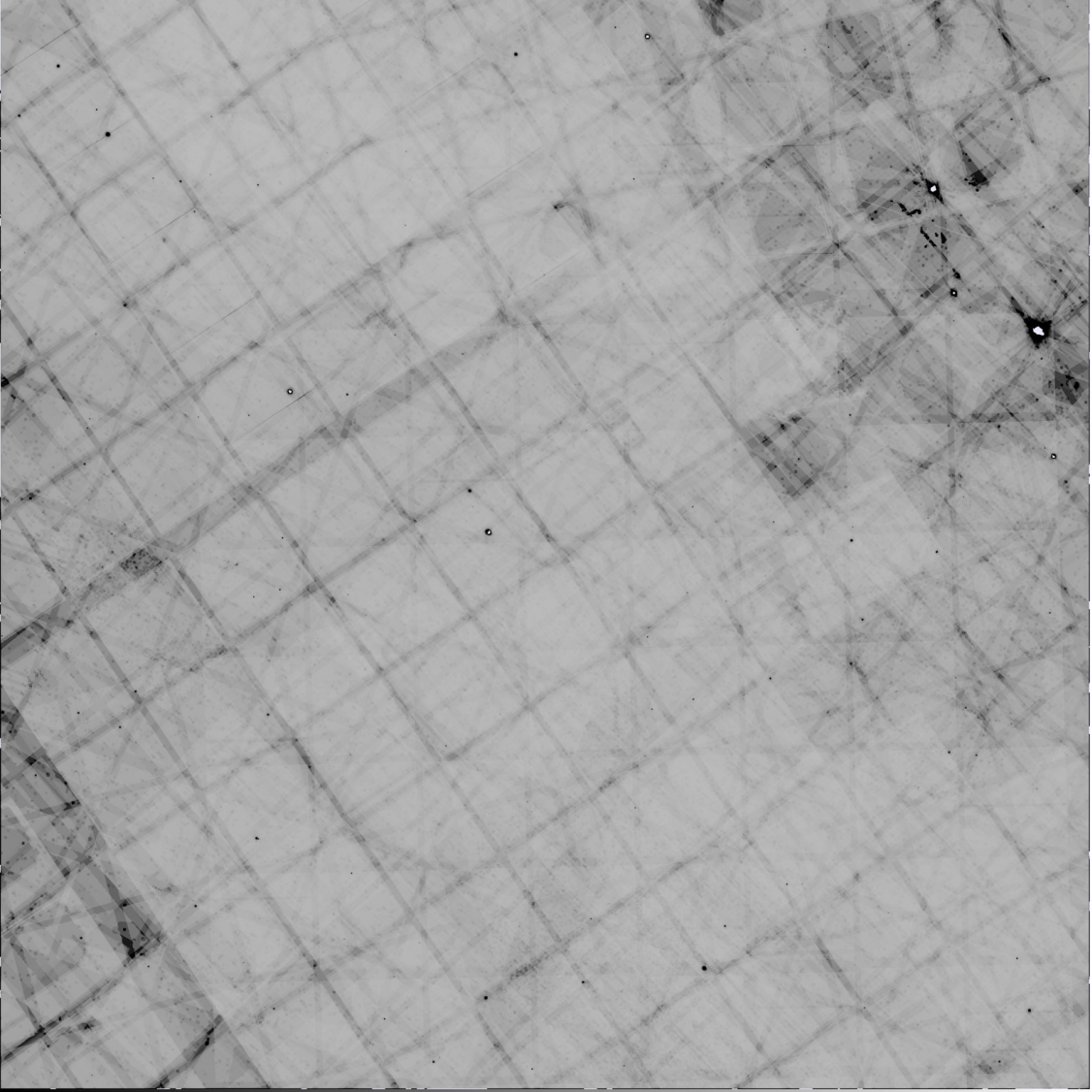


Fig. 19.— Example of the stack variance image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ in the z_{p1} filter, stack_id 3775944. The variance map for this stack is reasonably smooth, with the mottled pattern from the inter-chip and inter-cell gaps printing through. Some regions with higher variance are found where the number of inputs is lower.

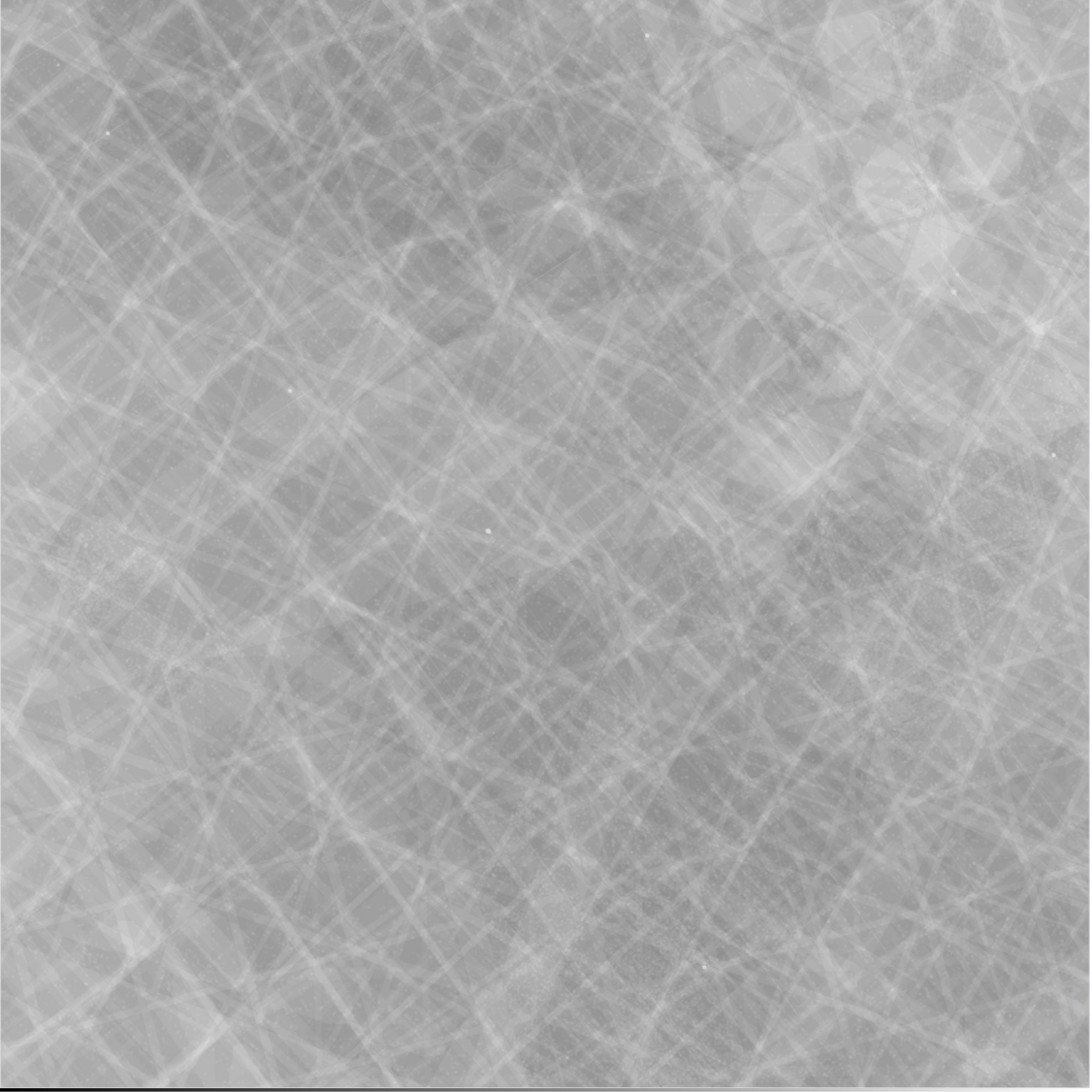


Fig. 20.— Example of the stack number image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ in the z_{P1} filter, stack_id 3775944. This map shows the number of inputs contributing to each pixel of the output stack. Again, the pattern of the inter-chip and inter-cell gaps is visible, along with the mask pattern of regions with CTE problems (visible in the upper right corner).

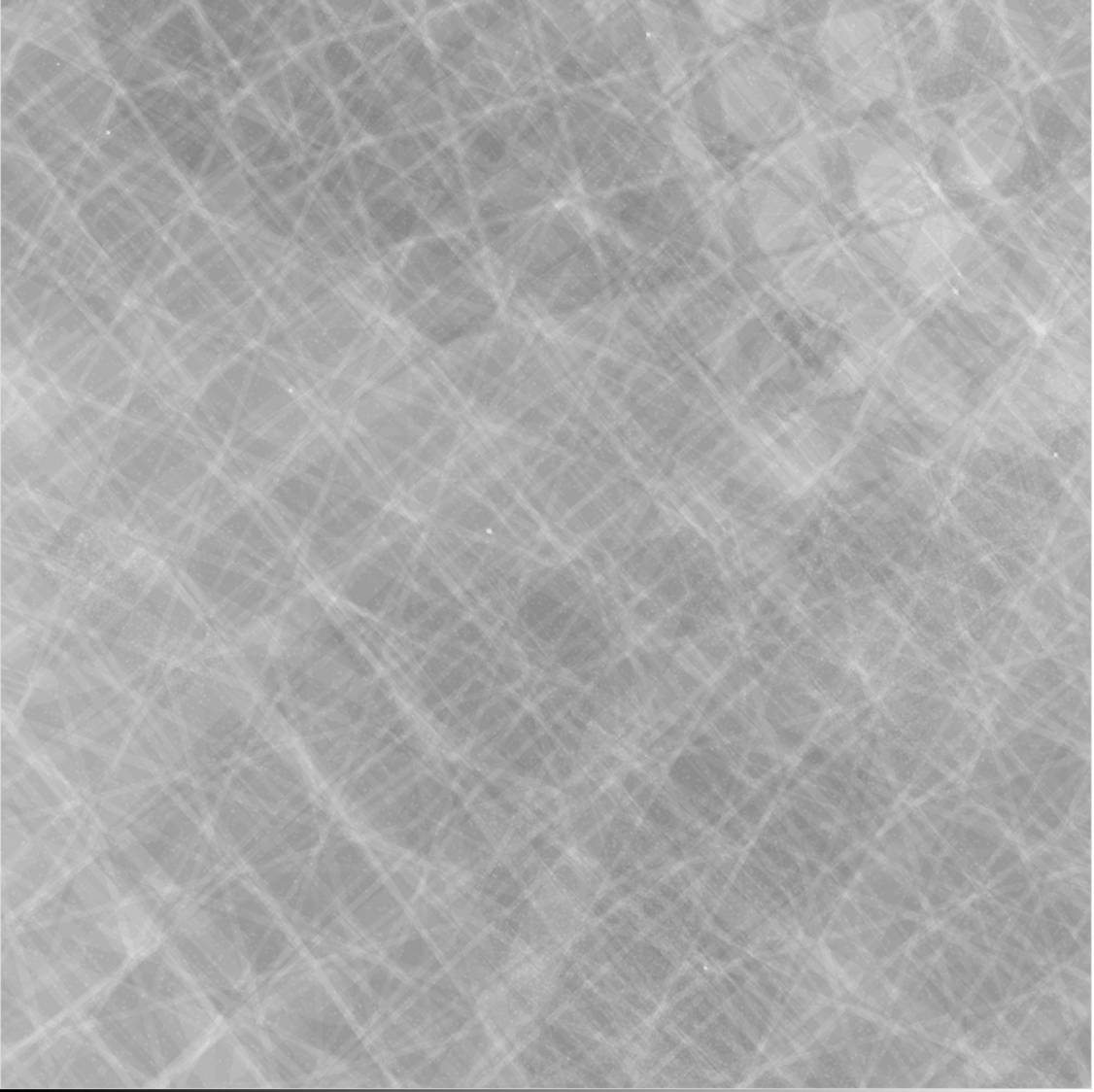


Fig. 21.— Example of the stack exposure time image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ in the z_{P1} filter, stack_id 3775944. As all input warps had the same 30s exposure time, this map essentially recreates the number map, with units of seconds of exposure instead of number of inputs contributing to a given pixel.

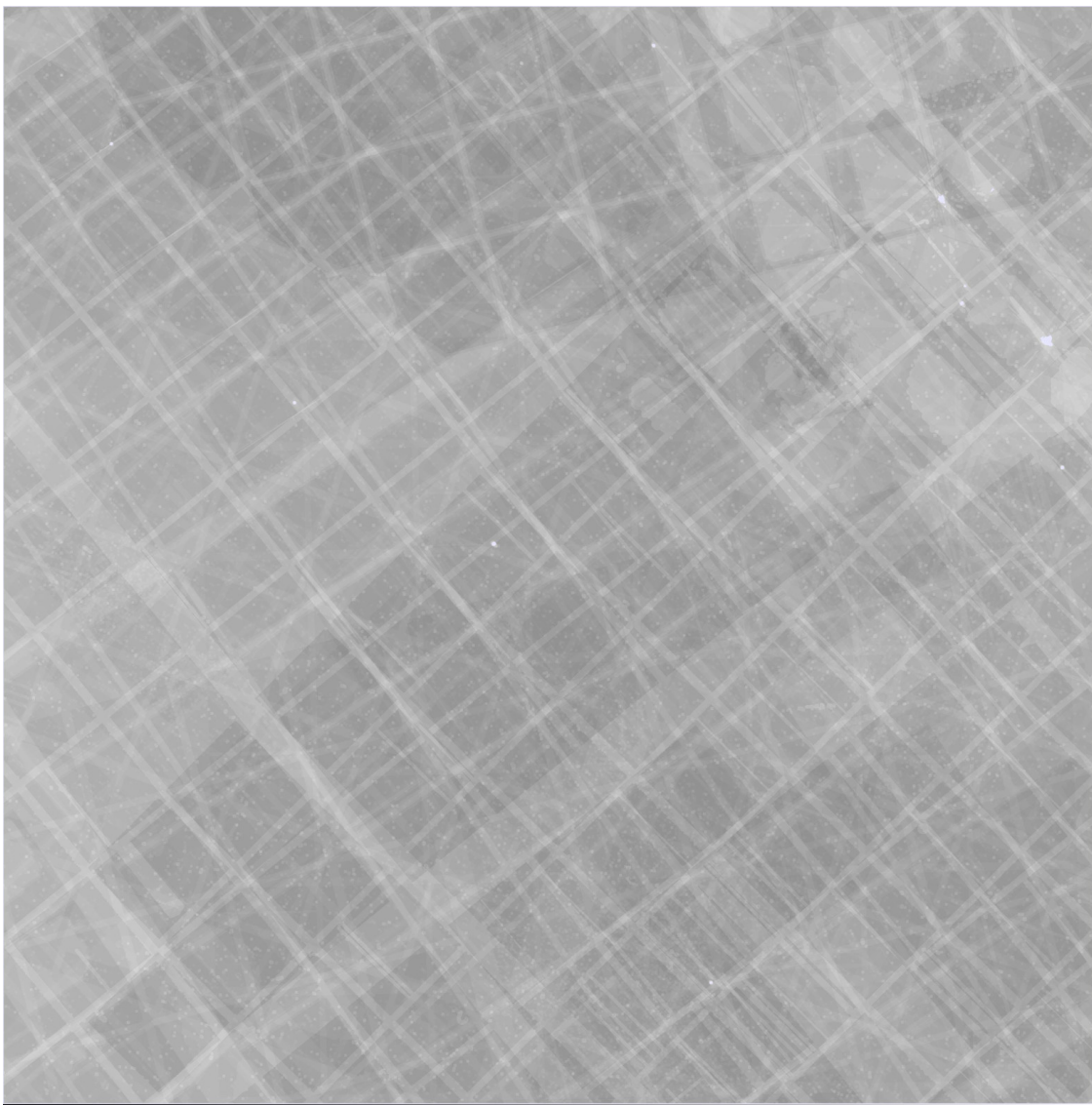


Fig. 22.— Example of the stack weighted exposure image for skycell skycell.2047.005 centered at $(\alpha, \delta) = (179.763, 32.1899)$ in the z_{P1} filter, stack_id 3775944. This map shows the weighted average exposure time, as described in the text. It is similar to the simple exposure time map, but shows how some input exposures have their contributions weighted down due to the observed larger image variances.

(completely in an ideal case), whereas sources that are not static between the two images leave a significant remnant. More information on the difference image construction is contained in Price et al. (2017). The follow section contains an overview of the difference image construction used for the data in DR2.

The images used to construct difference images can be either individual warp skycell frames or stacked images, with support for either to be used as the template or input. In general, for differences using stacks, the deepest stack (or the only stack in the case of a warp-stack difference) is used as the template. The PV3 processing used warp-stack differences of all input warps against the stack that was constructed from those inputs. The same ISIS kernels as were used in the stack image combination were again used to match the stack PSF to the input warp PSF. After convolution of the image products, the difference is constructed for both the positive (warp minus stack) and inverse (stack minus warp) to allow for the photometry of the difference image to detect sources that both rise and fall relative to the stack. Note that the convolution process grows the mask fraction of pixels relative to the warp (the largest source of masked pixels in these warp stack differences). Any pixel that after convolution has any contribution from a masked pixel is masked as well, ensuring only fully unmasked pixels are used.

For warp-warp differences, such as those used for the ongoing Solar System moving object search in nightly observations (Denneau et al. 2013), the warp that was taken first is used as the template. As there is less certainty in which of the two input images will have better seeing, a “dual” convolution method is used. Both inputs are convolved to a target PSF that is not identical to either input. This intermediate target is essential for the case in which the PSFs of the two inputs have been distorted in orthogonal directions. Simply convolving one to match the other would require some degree of deconvolution along one axis. As this convolution method by necessity uses more free parameters, the ISIS kernels used are chosen to be simpler than those used in the warp-stack differences. The ISIS widths are kept the same (1.5, 3.0, 6.0 pixel FWHMs), but each Gaussian kernel is constrained to only use a second-order polynomial. As with the warp-stack differences, the mask fraction grows between the input warp and the final difference image due to the convolution. For the warp-warp differences, each image mask grows based on the appropriate convolution kernel, so the final usable image area is highly dependent on ensuring that the telescope pointings are as close to identical as possible. The observing strategy to enable this is discussed in more detail in Chambers et al. (2017).

7. Discussion

Although the detrending and image combination algorithms work well to produce a consistent and calibrated images, having the full PV3 data set allows issues to be identified and solutions created for future improvements to the IPP pipeline. In addition, the existence of the final calibrated catalog can be used to look for issues that appear dependent on focal plane position.

An obvious way to make use of the PV3 catalog is to do a statistical search for electronic crosstalk ghosts that do not match a known rule. Given that bright stars do not equally populate all fields, choosing exposures to examine to look for crosstalk rules is difficult. The current crosstalk rules were derived from expectations based on the detector engineering, supplemented by rules identified largely based on unmatched transients. With the full catalog, identification of new rules can be done statistically, looking at detection pairs that appear more often than random.

There is some evidence that we have not fully identified all of these crosstalk rules, based on a study of PV3 images. For example, extremely bright stars may be able to create crosstalk ghosts between the second cell column of OTA01 and OTA21, with possibly fainter ghosts appearing on OTA11. Despite the symmetry observed in the main ghost rules, there do not appear to be clear examples of a similar ghost between OTA47 and OTA66. Examining this further based on the PV3 catalog should provide a clear answer to this, as well as clarify brightness limits below which the ghost does not appear.

The PV3 catalog may also allow better determination of which date ranges we should use to build the dark model. The date ranges currently in use are based on limited sampling of exposures, and do not have strong tests indicating that they are the best. By examining the scatter between the detections on a given exposure and the catalog average, we can attempt to look for increases in scatter that might suggest that the dark model used is not completely correcting the camera. Looking at this based on the catalog would allow this information to be generated without further image level processing.

In addition to improving the quality of the catalog for any future reprocessing, there are a number of possible improvements that could fix the image cosmetics. A study of the burntool fits on stars that have been badly saturated suggest that we may be able to improve the trail fits by considering not the star center, but rather the edge of saturation. This restricts the fit to only consider the data along the trail, and may improve the fit quality. Implementing this change would require additional bookkeeping of which pixels were saturated, as the fits on subsequent exposures will need to skip these pixels before fitting the persistence trail. This is unlikely to seriously impact the photometry of objects,

but may improve the results of stacks if fewer pixels need to be rejected.

The fringe model used currently is based on only a limited number of days of data. This means that the model calculated may not be fully sensitive to the exact spectrum of the sky. This may make the model quality differ based on the date and local time of observation. There is some evidence that the fringe model does fit some dates better than others, and so improving this by expanding the number of input exposures may improve a wider range of dates.

Finally, a large number of issues arise due to the row-to-row bias issues. The PATTERN.ROW correction is used on a limited number of cells, to minimize any possible distortion of bright stars or dense fields by the fitting process. As the row-to-row bias changes very quickly in the y pixel axis and slowly along the x, it may be possible to isolate and remove this signal in the Fourier domain. Preliminary investigations have shown that there is a small peak visible in the power spectrum of a single cell, but determining the optimal way to clip this peak to reduce the noise in the image space is not clear.

8. Conclusion

The Pan-STARRS1 PV3 processing has reduced an unprecedented volume of image data, and has produced a catalog for the 3II Survey containing hundreds of billions of individual measurements of three billion astronomical objects. Accurately calibrating and detrending is essential to ensuring the quality of these results. The detrending process detailed here produces consistent data, despite the many individual detectors and their individual response functions.

From these individual exposures, we are able to construct images on common projections and orientations, further removing the particulars of any single exposure. Furthermore, by created stacked images, we can determine an estimate of the true static sky, providing a deep data set that is ideal for use as a template for image differences.

The Pan-STARRS1 Surveys (PS1) have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, and the National Aeronautics and Space Administration

under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation Grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), and the Los Alamos National Laboratory.

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